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1917-1992

75 Years

NACA NASA Langley Research Center

75th Anniversary Publications
Historic NACA Technical Reports
NASA Magazine Summer 1992
Langley Anniversary Edition

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Established in 1917, NASA Langley Research Center has been on the forefront of air and space flight since shortly after the Wright brothers' historic flight. America's manned space program began here, and the Center has been involved in many well-known air and space projects, from breaking the sound barrier to the landing of men on the moon, the Viking landing on Mars, the Space Station Freedom, and the pioneering technology for the Space Shuttle and National Aero-Space Plane. The Center also is applying its massive technological capability to one of the world's most pressing concerns, the study of the Earth's fragile atmosphere.

NASA Langley celebrated its 75th Anniversary in 1992. These products were created during the diamond anniversary to tell the rich and varied history of America's first civil aeronautical laboratory. NASA was chartered in 1958 to provide for the "widest practicable and appropriate dissemination of information concerning its activities and results thereof."

This collection has been assembled in the spirit of that charter.

J. Campbell Martin

J. Campbell Martin
Head, Office of Public Affairs

NASA Langley Research Center expresses its thanks to:

Sport Aviation magazine, which gave its permission to reprint "The Mustang Story: Recollections of the XP-51," by Jack Reeder NACA/NASA test pilot. September 1983 Edition.

Wings magazine, which gave its permission to reprint "Testing the First Supersonic Aircraft, Memoirs of NACA Pilot Bob Champine," excerpted from the February 1991 Edition.

Dr. James R. Hansen, Langley historian and author of *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958,* who contributed the text of the majority of these publications, wrote the introductions to the NACA Technical Reports, and played a major role in verifying information.

Richard P. Layman, Langley historian, who contributed to the review process of these publications.

Kristina Murden, Langley Office of Public Affairs, who produced the NASA Facts publications.

James Shultz, who wrote *NASA Magazine's* Summer 1992 cover story, "Happy Birthday Langley!" Mr. Shultz is also the author of *Winds of Change*, Langley's 75th Anniversary capstone product.

Wesley Berryman, Langley retiree and calligrapher of the NACA Charter.

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in order of appearance

LAW ESTABLISHING THE NACA

Public Law 271, 63rd. Congress approved March 3, 1915

An Advisory Committee for Aeronautics is hereby established, and the President is authorized to appoint not to exceed twelve members, to consist of two members from the War Department, from the office in charge of military aeronautics; two members from the Navy Department, from the office in charge of naval aeronautics; a representative each of the Smithsonian Institution, of the United States Weather Bureau, and of the United States Bureau of Standards; together with not more than five additional persons who shall be acquainted with the needs of aeronautical science, either civil or military, or skilled in aeronautical engineering or its allied sciences: Provided, that the members of the Advisory Committee for Aeronautics, as such, shall serve without compensation: Provided further, That it shall be the duty of the Advisory Committee for Aeronautics to supervise and direct the scientific study of the problems of flight, with a view to their practical solution, and to determine the problems which should be experimentally attacked, and to discuss their solution and their application to practical questions. In the event of a laboratory or laboratories, either in whole or in part, being placed under the direction of the committee, the committee may direct and conduct research and provided further, That rules and regulations for the conduct of the work of the committee shall be formulated by the committee and approved by the President.

That the sum of $5,000 a year, or so much thereof as may be necessary, for five years is hereby appropriated, out of any money in the Treasury not otherwise appropriated, to be immediately available, for experimental work and investigations undertaken by the committee, clerical expenses and supplies, and necessary expenses of members of the committee in going to, returning from, and while attending, meetings of the committee: Provided, That an annual report to the Congress shall be submitted through the President, including an itemized statement of expenditures.

NASA Facts

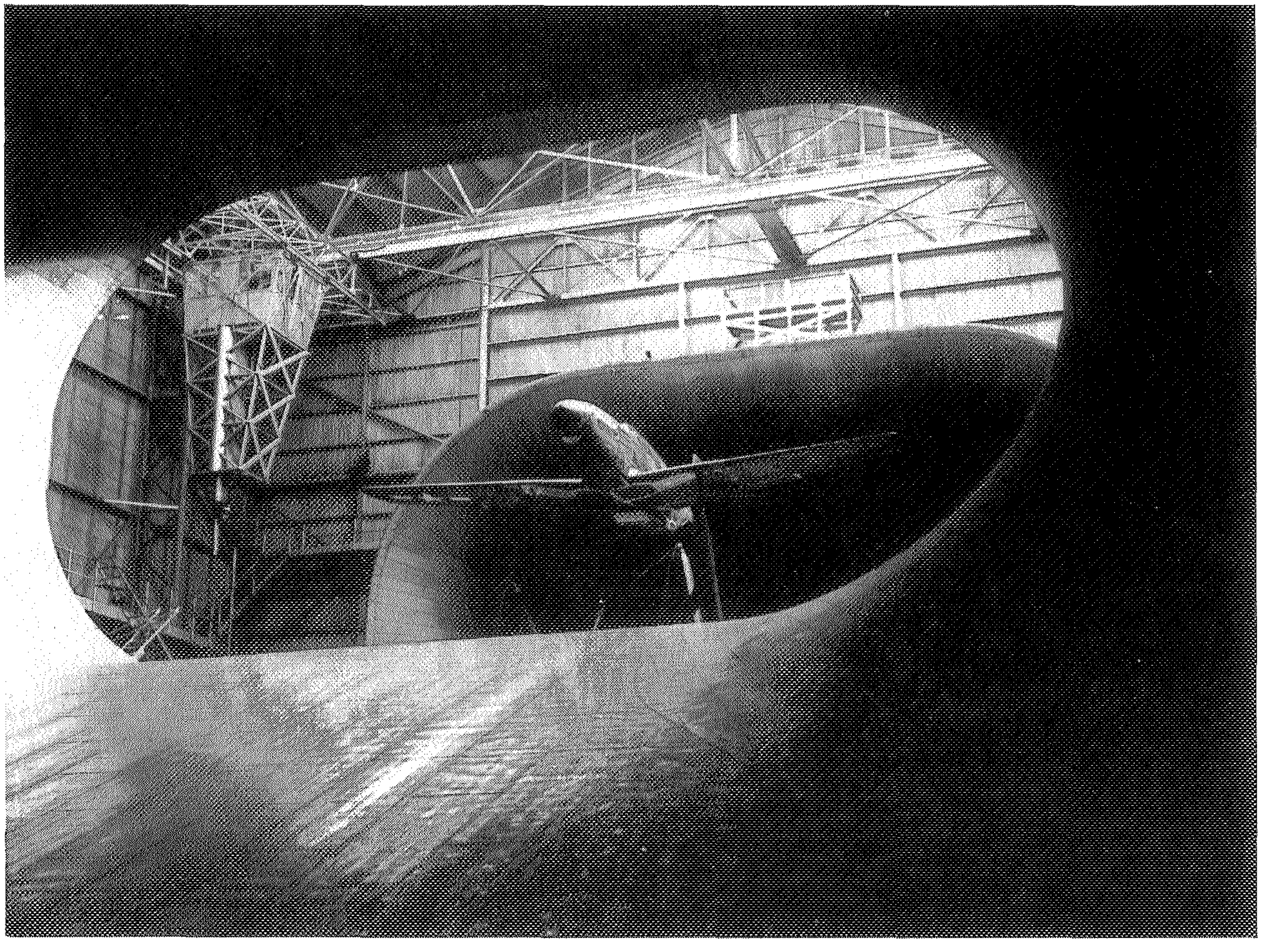
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

NF167 - April 1992

Exploring NASA's Roots

The History of Langley Research Center



North American's P-51 Mustang, the first aircraft to use the NACA laminar flow airfoil, is tested at Langley Research Center in 1943 in the world's first full-scale wind tunnel.

We are rapidly approaching the dawn of a new century, the 21st, and a new millennium, the third in the Christian era. In the last hundred years humankind has moved from the dim glow of the first electric light bulb to the cold cloud of the superconductor, from the clatter of the steam-powered railroad locomotive to the roar of the supersonic jet airliner. In the last thousand we have progressed from the water wheel to the fusion reactor, from the ox-cart to the Space Shuttle. Only a clairvoyant could have forseen the course of our development. It will take an even bolder visionary to imagine where we shall end up 100 years from now, let alone 1,000. Our rate of change, already invisibly rapid, seems only to be picking up.

In the field of aerospace technology the developments of the next century should be spectacular. The regularly scheduled flights of supersonic airliners and hypersonic aircraft capable of flying in and out of the atmosphere should enable the peoples of the world to join together on a veritable global village. No spot in the world should be farther away than two hours traveling time—or perhaps even less. There should be permanent outposts on the Moon. We should visit Mars and venture out to even more remote bodies of the solar system.

New scientific discoveries will change radically our understanding of the universe and our place in it. Perhaps signs of other life in the universe will be discovered.

All of these things might very well happen in the "Second Century" of powered flight. If they do, it will be because the next generations of aerospace scientists and engineers will be standing, in Isaac Newton's words, on the shoulders of giants.

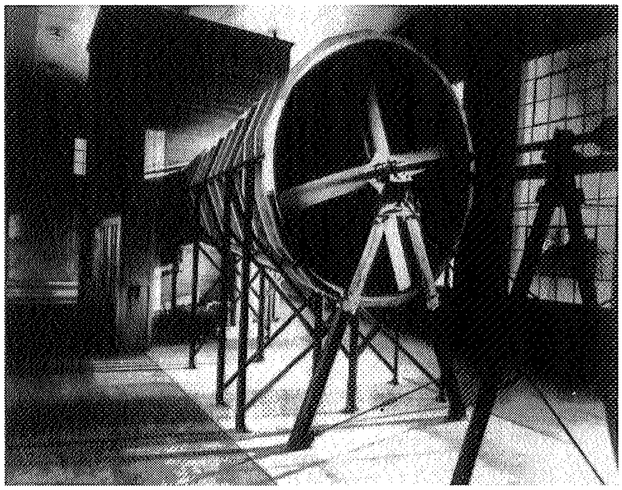
This NASA Facts explores the history of NASA Langley Research Center in Hampton, Virginia, this country's first civilian aeronautics laboratory. Several major episodes in the epic story of American aerospace have their roots in the research contributions made by Langley since its establishment in 1917. The following is a brief synopsis of Langley's most historically significant achievements.

Back to the days of NACA

Today's National Aeronautics and Space Administration (NASA) was established in 1958, but its historical roots reach back much farther, to 1915. In that year, 12 years after the Wright Brothers' flight and two years before American entry into World War I, the U.S. Congress created the National Advisory Committee for Aeronautics, or NACA.

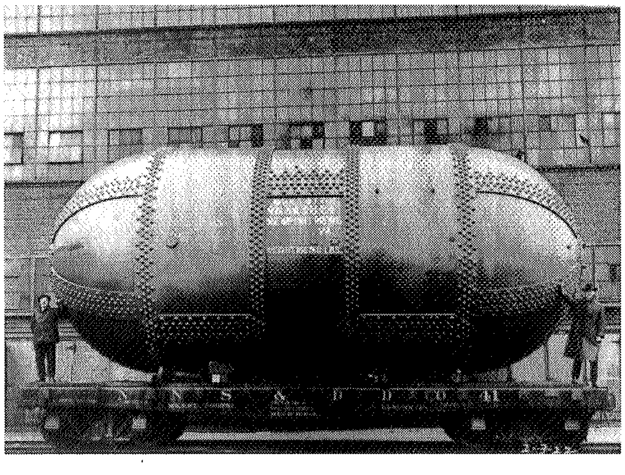
In 1915 the airplane was still largely a useless freak. Much had to be done to transform it into a practical and versatile vehicle. The NACA's mission was "to supervise and direct the scientific study of the problems of flight with a view to their practical solution." This meant that the NACA was to treat aeronautics not so much as a scientific discipline, but as an area for engineering research and development. In practice this turned out to mean that the NACA would perform basic research that provided "practical solutions" to serious problems facing the aircraft industry and the military air services.

Although established in 1915, the NACA did not have operational laboratory facilities until 1920, when Langley came on line with its first primitive wind tunnel. Construction of Langley Field actually began in 1917, but the chaos of mobilizing for war in Europe delayed completion of the NACA's facilities for three years.



Langley Laboratory's first wind tunnel, built in 1920.

Once in possession of effective experimental equipment, however, the laboratory pursued its mission with distinction. Already by the end of



Put into operation at Langley in 1922, the Variable Density Tunnel was the first pressurized wind tunnel in the world. It could achieve more realistic effects than any previous wind tunnel in predicting how actual aircraft would perform under flight conditions. Today it is a National Historic Landmark.

the 1920s, with its ingeniously designed Variable-Density Tunnel, Propeller Research Tunnel, and Full-Scale Tunnel, which outperformed any other single collection of facilities anywhere in the world, NASA Langley was generally acknowledged to be the world's premier aeronautical research establishment. Thanks to the reliable data resulting from intelligent use of Langley's unique complex of experimental equipment, American aircraft began to dominate the world's airways.

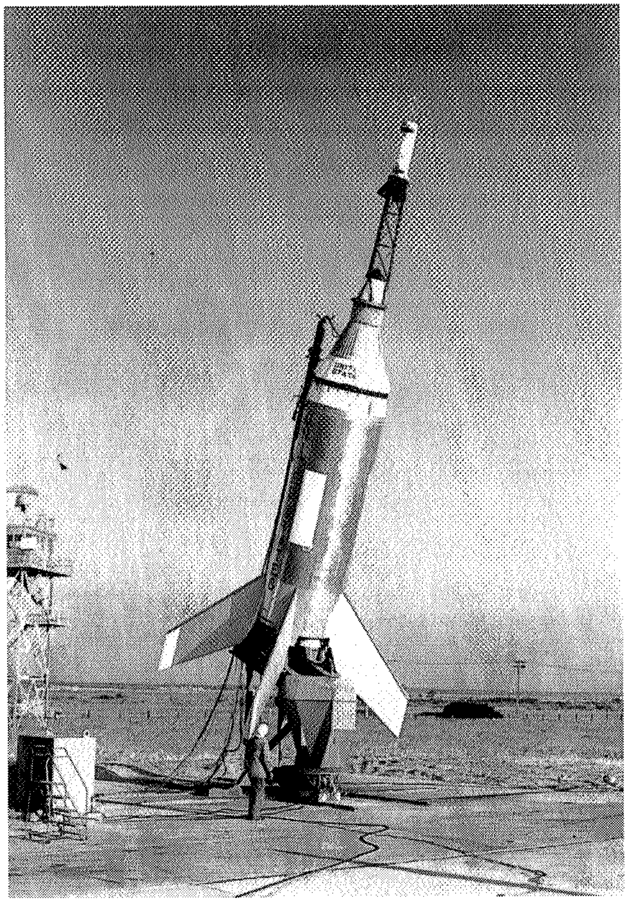
Through systematic aerodynamic testing, NACA researchers found practical ways to improve the performance of many different varieties of aircraft. During World War II, they tested virtually all types of American aircraft that saw combat. By pointing out ways for these aircraft to gain a few miles per hour or a few extra miles of range, their effort in many cases made the difference in performance between Allied victory and defeat in the air.

After the war, NACA researchers turned their attention to the high-speed frontier and solved many of the basic problems blocking the flight of aircraft to supersonic speeds. They played essential roles in the development of several experimental high-speed research airplanes including Bell's X-1, the first plane to break the sound barrier, and the North American's X-15, the first winged aircraft to fly into space.

The NACA flourished as a federal agency until the autumn of 1958, when it was formally abolished. In truth, however, much about the NACA lived on. Its laboratories and their staffs, although reorganized, formed the nucleus for the new space agency. The rest is history—NASA history.

The Space Frontier

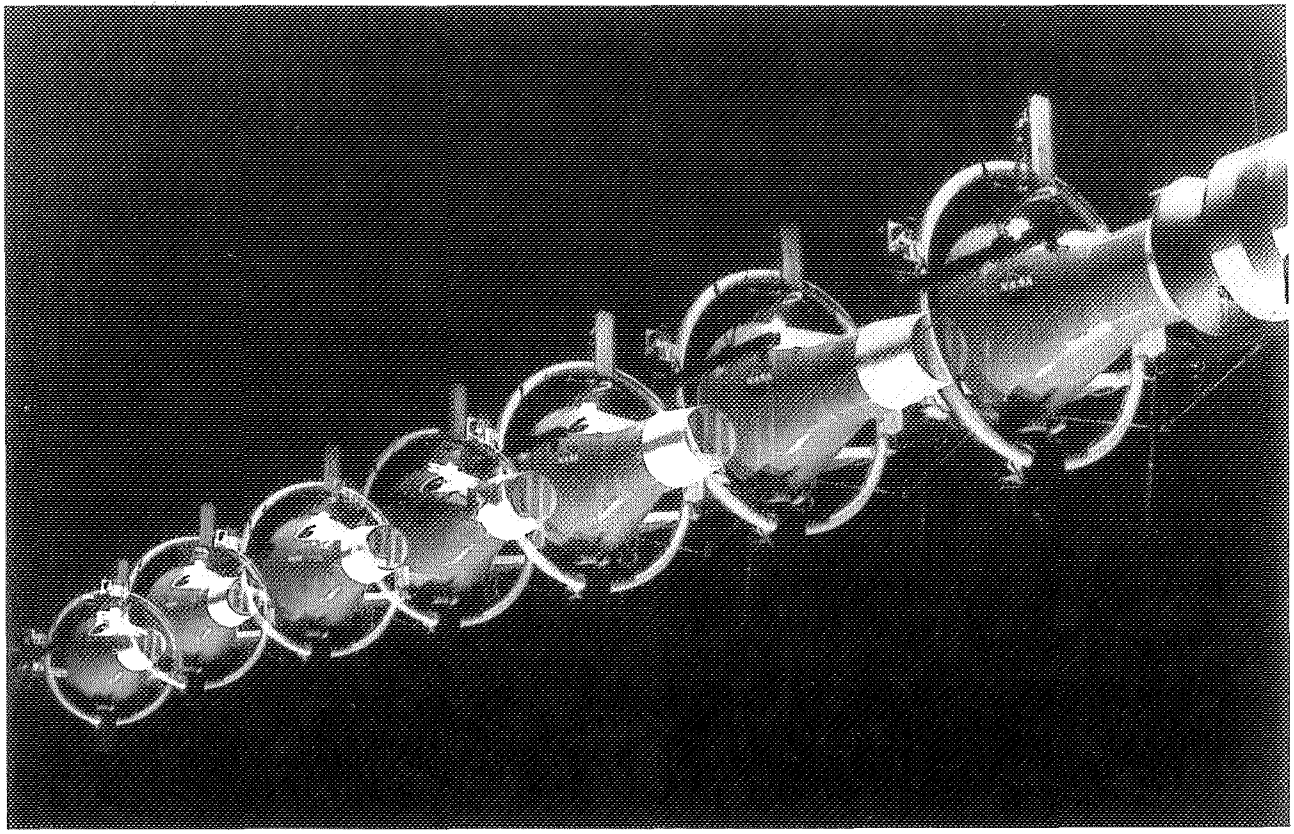
Although its name changed in 1958 from NACA Langley Aeronautical Laboratory to NASA Langley Research Center, the mission of its staff members remained constant: to increase the country's knowledge and capability in a full range of aeronautical disciplines and in selected space disciplines.



Project Mercury's "Little Joe" launch vehicle, January 13, 1960, Wallops Island, VA. Little Joe, managed by Langley, demonstrated the Mercury capsule configuration and did much to ensure the dependability of the Mercury capsule's escape system and parachutes.

In the early 1960s Langley helped give birth to the space age. Project Mercury, the nation's inaugural man-in-space program, was conceived and managed initially from Langley. Spear-heading this effort was the Center's Space Task Group, a special force of NASA employees that later expanded and moved on to become the Manned Spacecraft Center (now Johnson Space Center) in Houston. Before their move to Texas, however, they led the original seven astronauts (Shepard, Grissom, Glenn, Carpenter, Slayton, Schirra, and Gordon) through the initial phases of their spaceflight training at Langley.

NASA's seven original astronauts trained at Langley. Posed in front of a Convair F-106, they are (left to right): Scott Carpenter, Gordon Cooper, John Glenn, Gus (Virgil) Grissom, Walter Schirra, Alan Shepard, and Donald Slayton.

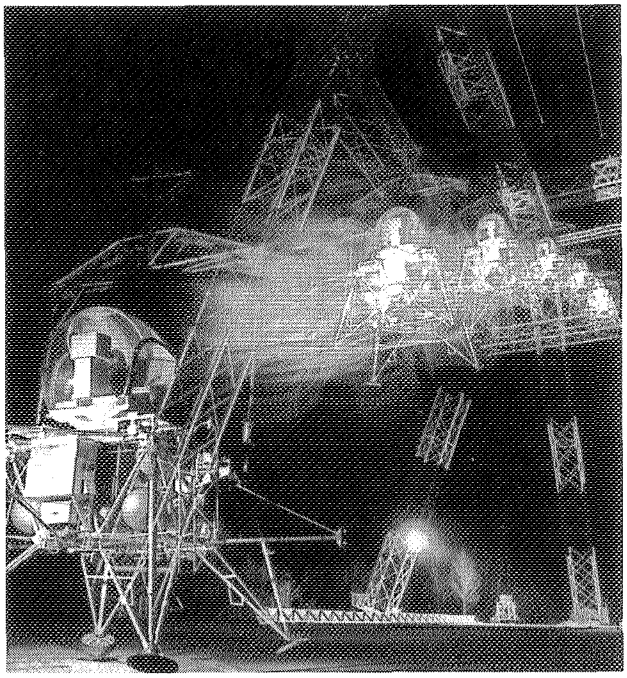


Rendezvous and docking in space were tested and practiced at Langley with free-moving vehicles suspended on cables with the Rendezvous Docking Simulator, now a National Historic Landmark. Here it is being used to simulate conditions to be found during the Gemini-Agena missions.

NASA Langley went on to make several essential contributions to the Mercury, Gemini, Apollo, and Skylab manned programs. A thoughtful group of engineers at the Center proved the feasibility of lunar-orbit rendezvous (LOR). Without the articulation of this successful mission concept, the United States may have still landed men on the Moon, but it probably could not have happened as soon as it did, before the decade of the 1960s ran out, as President Kennedy had proposed.

Spaceflight simulators designed and operated at the Center gave NASA's astronauts the experience they needed to pilot their fragile craft through the many difficult challenges of rendezvous and docking in space and landing on the Moon. The high-resolution photographic maps of the lunar surface made by NASA Langley's Lunar Orbiters made it possible to select the best sites for the landings of the Apollo and Surveyor spacecraft, and thereby learn more about the nature of the Moon.

Early unmanned space projects involving considerable creative effort by NASA Langley researchers included the Echo, Explorer, and



During a nighttime training session, a multiple exposure captures the movement of the Lunar Excursion Module, a manned simulator designed to familiarize the Apollo astronauts with handling characteristics of a lunar-landing type vehicle.

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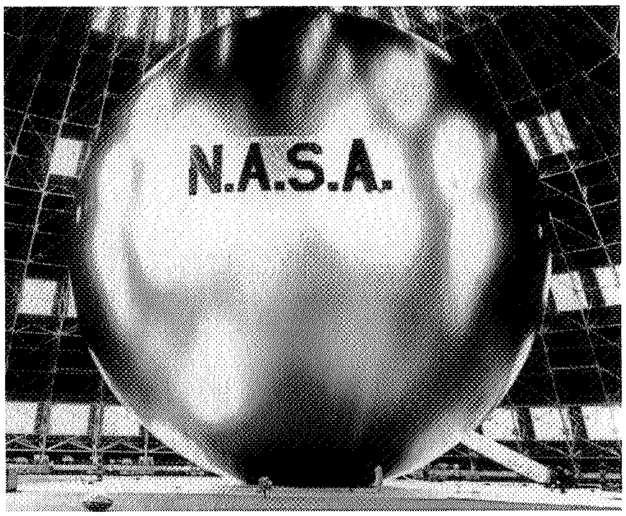
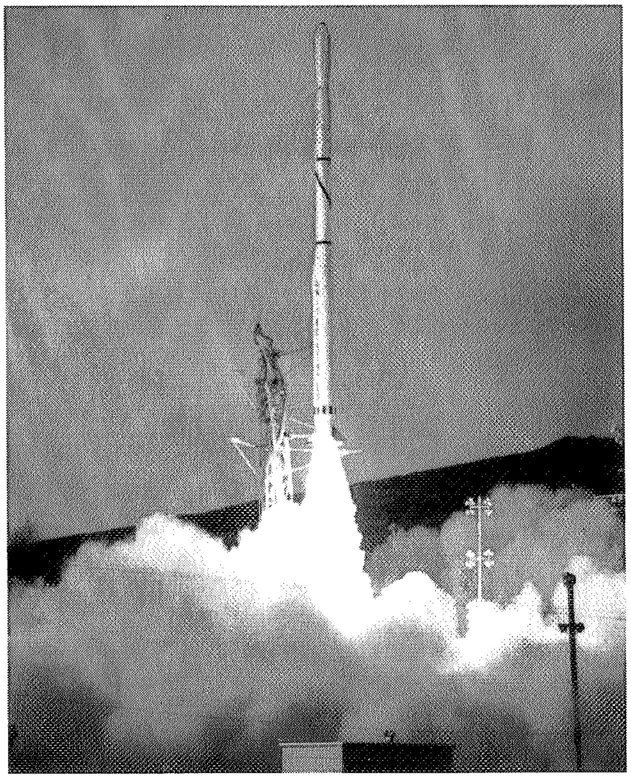


Conceived at Langley, the Echo communications satellite, designed to reflect radio and radar signals, undergoes an inflation test in 1959. Echo was the world's first passive communications satellite.

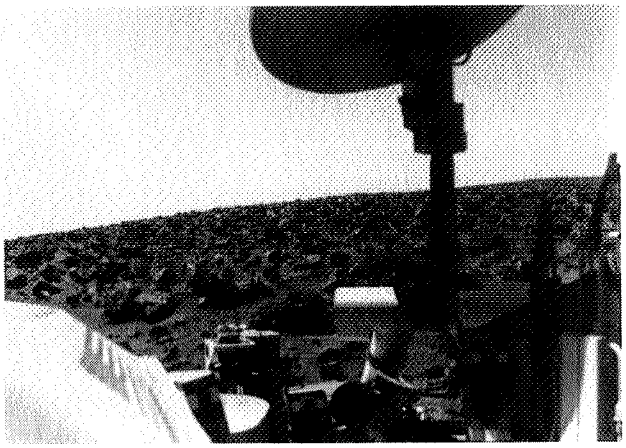
PAGEOS satellites, all of which gave outstanding service as instruments for scientific research and global communications.

A solid-fuel rocket developed at the Center, the Scout, provided NASA with its lowest-cost, multipurpose booster. With it, a great number of precious payloads were launched into orbit. The first Scout was launched in July 1960.



1988 launch of the highly-successful Scout launch vehicle, used for unmanned small satellite missions, high-altitude probes and reentry experiments. Scout was managed by Langley from 1957-1991.

In the wake of the Apollo came Viking. In an effort that in many ways matched and even surpassed the magnitude and adventure of the lunar landing program, NASA Langley helped to send two orbiters and two landers in the mid-1970s to the planet Mars. Although probes did not result in any definitive answer to the question of whether life exists (or has ever existed) on the mysterious red planet, Viking nonetheless provided a wealth of valuable scientific information.

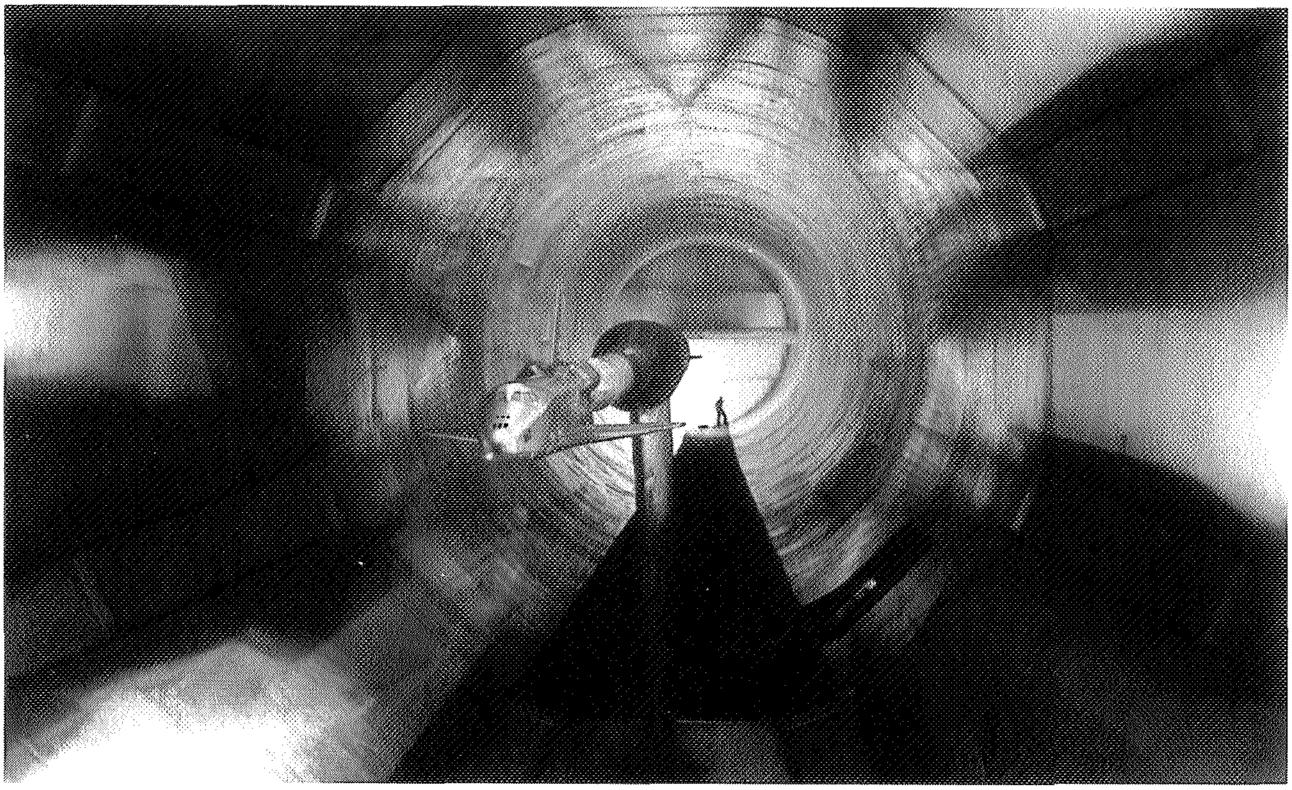


The Langley managed Viking 2 lander on Mars' Utopian Plain, September 24, 1976 - America's 200th Birthday year.

In response to a growing concern in the late 1960s for protection of our environment, Langley researchers began to develop effective means by which to measure the Earth's oceans and continents, and detect the presence of dangerous pollutants. This effort in environmental space science quickly became a major research thrust at the Center. Its goal has been to preserve the Earth's precious ecological balance and prevent an environmental calamity that would have disastrous effects for the entire world. Today at Langley this critically important undertaking is part of what former NASA astronaut Sally Ride has called "Mission to Planet Earth."

An important contribution to this "mission" includes Langley's Halogen Occultation Experiment (HALOE), an atmospheric satellite deployed by the Space Shuttle in 1991. Its overall goal is to provide global-scale data on temperature, ozone, and other key trace gases needed to study and better understand the chemistry, dynamics and radiative processes of the middle atmosphere.

Langley researchers had thought about "space planes" since the early 1950s. They had

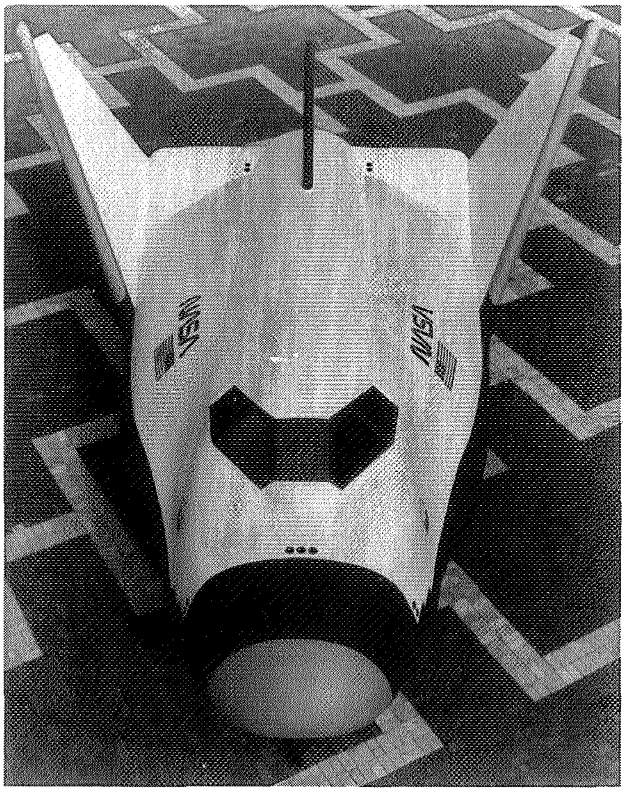


What may appear at first glance to be a swimming shark is a wind tunnel model of the Space Shuttle orbiter, tested in Langley's 16-Foot Transonic tunnel in 1978 for aerodynamic reentry characteristics.

pioneered the concept of the boost glider and provided basic concepts for the development of the X-15, America's first hypersonic transatmospheric vehicle. So it was natural for them to become deeply involved in the development and testing of NASA's Space Shuttle. Even before it could be test flown in 1977 (its first orbital flight took place in 1981), the Shuttle had to be put through thousands of hours of wind tunnel testing and other rigorous experiments. Much of this was done at Langley. Furthermore, Langley was responsible for optimizing the design of the Shuttle's thermal protection system, the unique arrangement of ceramic tiles that protect the reusable vehicle from the intense heat of reentry.

To complement the Space Shuttle system and provide assured manned access to space for the next generation of space programs, Langley has conceived the HL-20 lifting body as a candidate for the Personnel Launch System (PLS). This system was designed for the primary mission of changing the Space Station Freedom crews.

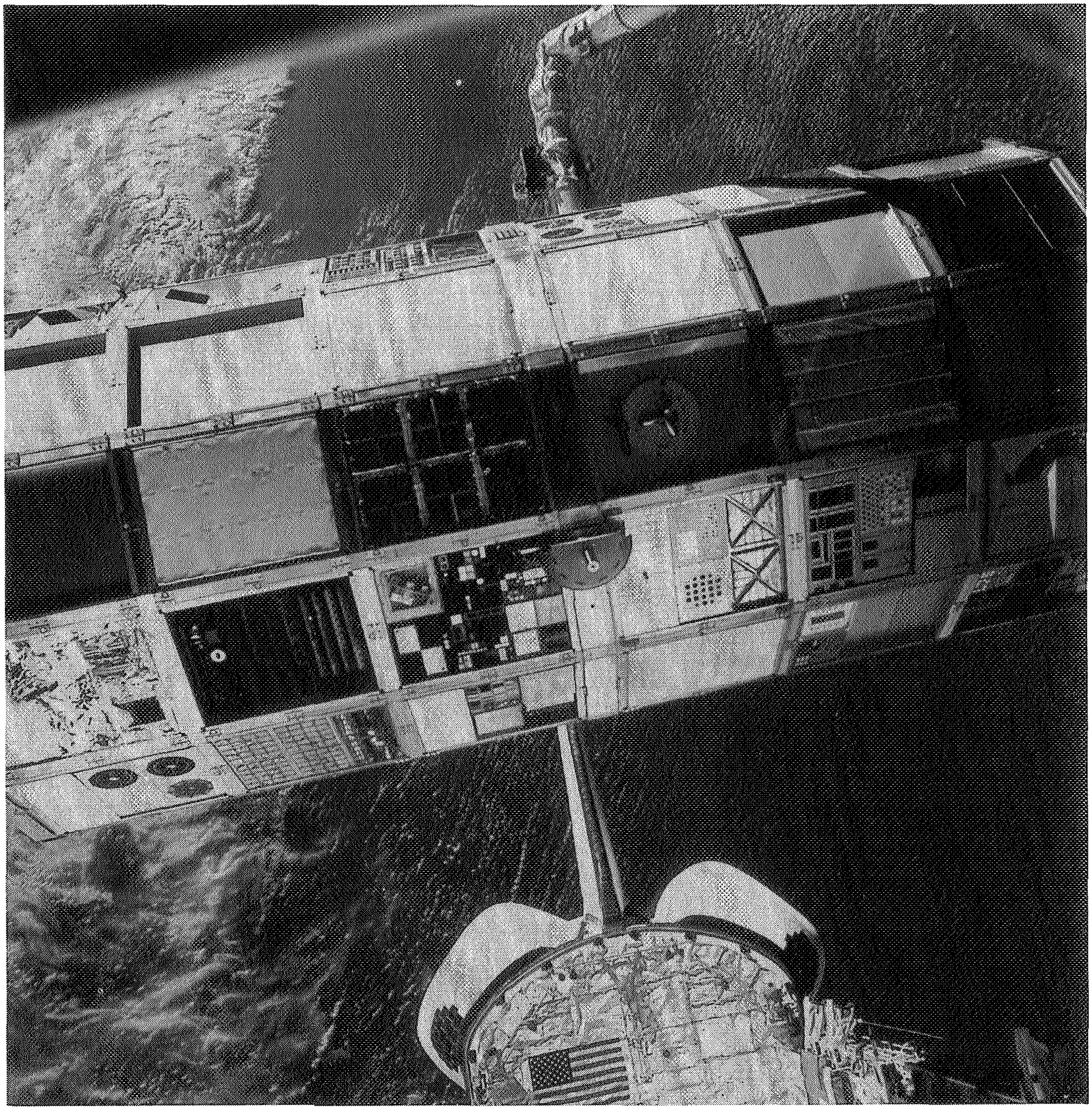
Visions of space stations orbiting the Earth had captured the imaginations of many Langley researchers as well. Long before plans for today's Space Station Freedom got under way, NASA scientists and engineers at the Center had under-



The HL-20 "space taxi" was conceived as a candidate vehicle to complement the Space Shuttle, designed for the primary mission of changing the Space Station Freedom crews.

stood the advantages of a manned laboratory in space for scientific experiments, for communications, for astronomical observation, for manufacturing, and as a relay base for lunar and planetary missions, and many other purposes. Excited by the thought of a multipurpose laboratory, they began to explore the problems of designing such a facility and operating it in Earth orbit. This early brainstorming and testing has provided a solid basis for NASA's development of Space Station Freedom. Today Langley employees continue to investigate the technologies that will be necessary for the design and operation of the Space Station, as well as for other large space structures.

One such step was the deployment and retrieval of the Long Duration Exposure Facility (LDEF), which was conceived, designed and developed at Langley. The bus sized satellite carried 57 space experiments to gather scientific data and to test the effects of long-term space exposure on spacecraft materials, components and systems. The wealth of information collected during its six-year journey will be invaluable for the design of future spacecraft.



LDEF carried 57 experiments into low-Earth orbit for six years. On board were more than 10,000 items to test the effects of long-term space exposure on spacecraft materials, components, and systems. Pictured is its 1990 retrieval by the Space Shuttle Columbia.

Continuing a Tradition of Excellence in Aeronautics

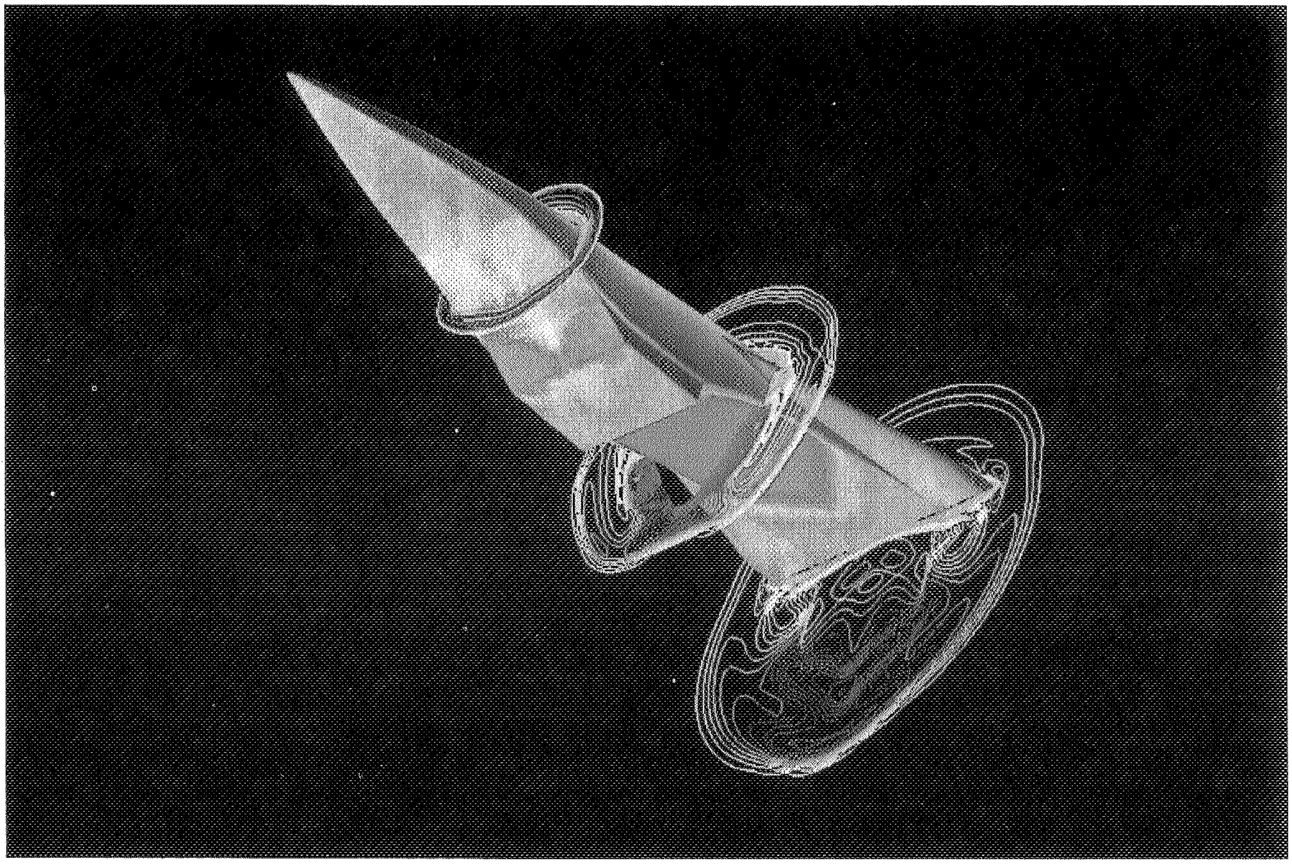
With deep roots going back to the golden age of aviation, Langley Research Center never forgot that the first "A" in NASA stood for "aeronautics." Although its achievements in aeronautics were sometimes overlooked in favor of the glories and wonders of spaceflight, NASA Langley not only maintained its historic position as a world leader in aeronautical research it actually built and improved upon it.

During the 1960s Langley scientists and engineers put in a mammoth, Apollo-like effort in support of the government's proposed, but later cancelled, construction of a national supersonic transport or SST. Concurrently, they explored the potential of the variable-sweep wing and other aerodynamically and structurally novel wing shapes both for the SST and for advanced performance military aircraft.

Noteworthy breakthroughs in aeronautics have included the improvement of vertical takeoff and landing (VTOL) capabilities; the design of the "supercritical wing" for more effective flight at high supersonic speeds; the enhancement of laminar flow in the boundary layer of a wing; and the refinement of energy-efficient engines and fuels. All of these research efforts—with the exception of SST, which was cancelled by the U.S. Congress in 1971—continued to yield valuable results into the 1970s and 1980s.

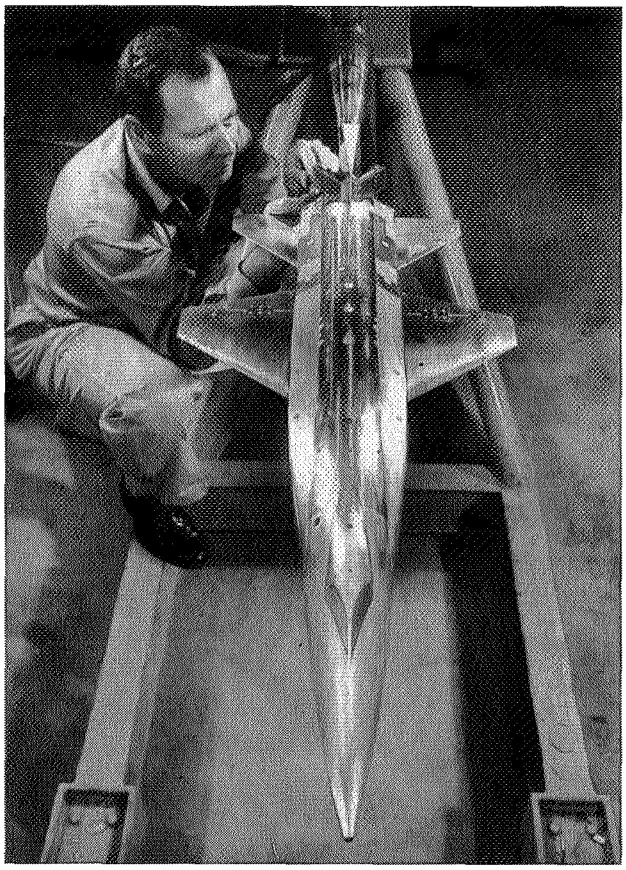
But even the supersonic work did not really come to an end. From the early 1970s on, Langley managed to keep alive a low-level but determined program to develop the technologies required for the effective flight of a supersonic transport. By the mid-1980s, there was a renewed interest at the Center in the development of an American SST. According to estimates, new technologies, including those developed at NASA Langley, now make an SST a much better bet.

In the 1970s Langley also kept the dream of hypersonic flight alive. This effort, which has important links back to studies made at Langley as early as the 1950s, now finds application in the National Aero-Space Plane (NASP). The focus of this program, in which Langley is the lead Center for its development, is to create the

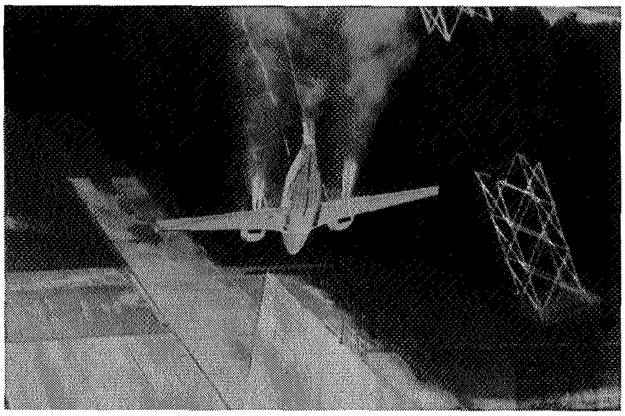


SRAMJET engine exhaust is modeled in this supercomputer-generated image of an aerospace vehicle as part of the National Aero-Space Plane (NASP) Program. Langley is the lead NASA Center for its development.

technology base for an entirely new family of aerospace vehicles capable of flying at high Mach numbers to the edges of the atmosphere and beyond. Under this program a single-stage-to-orbit flight vehicle, known as the X-30, might be flying by the end of this century.



A Langley technician inspects a wind tunnel model of the North American X-15 research aircraft. The X-15 was the first winged aircraft to fly into the fringes of space. (50 miles high)



A rocket assisted aircraft swings toward the concrete pad at the Langley Impact Dynamics Facility in a highly controlled crash test. The test was one of an extensive series conducted through the 1970s and early 1980s to document structural response to various impact conditions.

Langley has participated in too many significant aeronautical programs, in support of too many civilian and military aircraft development programs, to describe all of them in detail. The following list of selected programs—some completed in past years, some ongoing—should be enough to exhibit the value of the Center's wide-ranging aeronautical studies.

X-15 Program

Hypersonics

Lifting Bodies

Supersonic Cruise Aircraft Research

Quiet Engine Research

Vertical Short Takeoff and Landing Research

Aircraft Energy Efficiency

Advanced Turboprop

Composite Materials

Crash Dynamics

Forward Swept Wing

Automated Pilot Advisory System

Stall Spin Research

Advanced Controls

Rotor Inflow Research

Laminar Flow Control

Windshear

CRT's in Cockpits

Drag Reduction Studies-WW II

Historically, Langley researchers have found it beneficial to study these topics both in wind tunnels and other ground-based experimental facilities as well as in the actual flight test of aircraft. From the start, Langley's outstanding record in aerospace research has depended on creative use of basic research tools. Over the years Langley has built and operated an array of sophisticated facilities that collectively have not been outproduced by any other of the world's premier aeronautical research establishments. Many of its wind tunnels have been unprecedented. The U.S. Department of Interior has designated five of Langley's facilities as National Historic Landmarks.

Where the Past Once was . . . the Future is Now

From the Curtiss Jenny to the Beech Starship and X-29, from the drone of propellers to the roar of rockets and jets, from wind tunnels generating a maximum airflow speed of 90 miles per hour to tunnels generating Mach 8, from flight a few hundred feet above the ground to flight in space, Langley Research Center has been incubating the ideas and hatching the technology that has helped Americans take off and fly. Today, penetrating minds continue to pursue that mission at Langley. Tomorrow? Well, no one can be sure what tomorrow will bring. But based on what we know about Langley's record, one can rest assured that, where the progress of flight is concerned, NASA Langley Research Center will be exploring all the possibilities.

Basic Chronology

- *1915 Creation of the National Advisory Committee for Aeronautics (NACA), Langley's first parent organization.*
- *1917 Foundation of the NACA's Langley Memorial Aeronautical Laboratory (LMAL) and start of construction on original facilities.*
- *1920 Formal dedication of LMAL; operation of first wind tunnel.*
- *1948 Name shortened to Langley Aeronautical Laboratory (LAL).*
- *1958 Dissolution of NACA and foundation of National Aeronautics and Space Administration (NASA); name changed to Langley Research Center.*

Langley's National Historic Landmarks

In 1985 the U.S. Department of Interior designated five Langley facilities as National Historic Landmarks. Each facility made a unique and outstanding historical contribution to American achievements in flight technology.

Name of Facility	*Year Built*
Variable-Density Tunnel	*1921*
Full-Scale Tunnel	*1930*
8-Foot High-Speed Tunnel	*1935*
Rendezvous Docking Simulator	*1963*
Lunar Landing Research Facility	*1965*

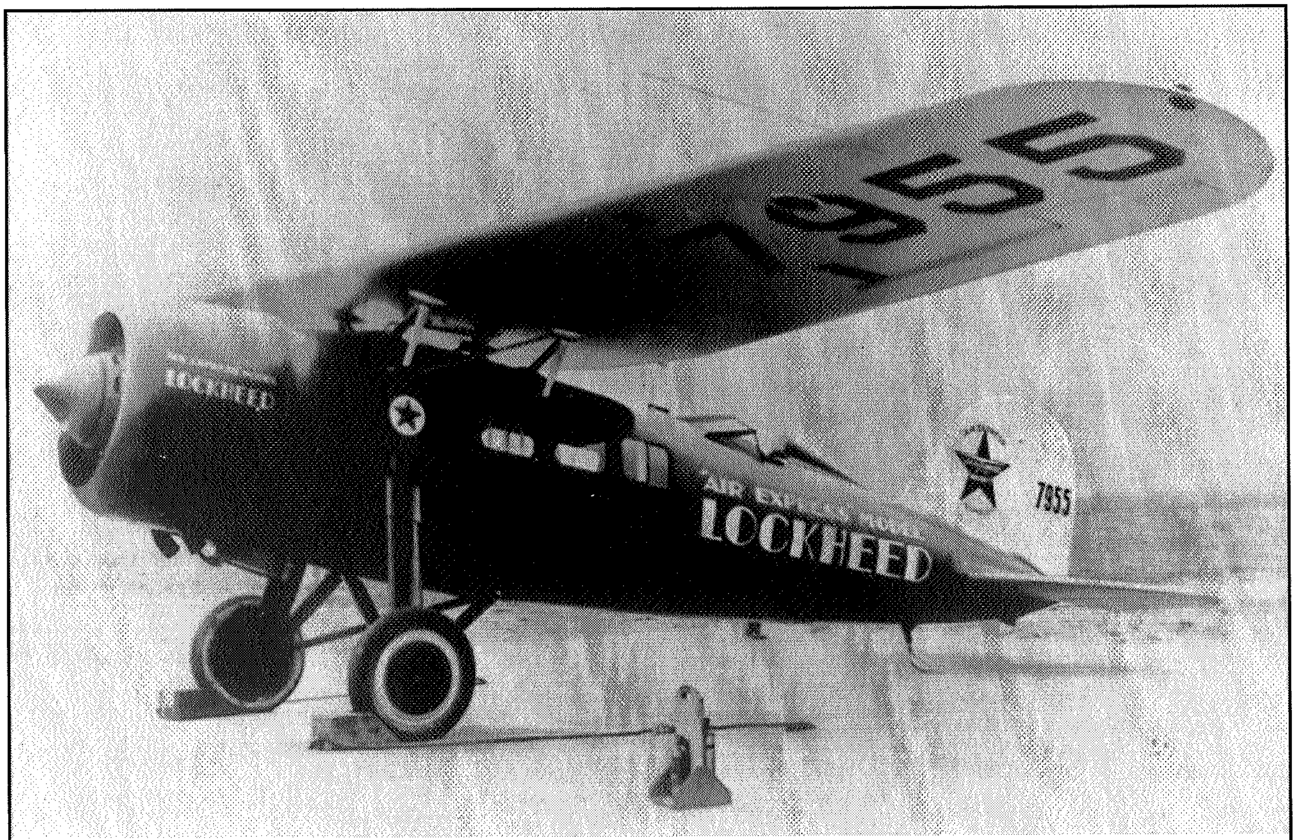
Langley Directors

In all of Langley history there have been only seven directors. Until 1948 this officer, Langley's top man, was known by the descriptive title, "Engineer in Charge."

Leigh H. Griffith	*(1922-1925)*	*Donald P. Hearth*	*(1975-1985)*
Henry J.E. Reid	*(1926-1960)*	*Richard H. Petersen*	*(1985-1991)*
Floyd L. Thompson	*(1960-1968)*	*Paul F. Holloway*	*(1991-)*
Edgar M. Cortright	*(1968-1975)*		

Collier Trophies

Although NASA Langley has been honored to receive a number of national awards and international distinctions, over the years many have considered one award, the Robert J. Collier Trophy, to be the most prestigious. Awarded annually for the greatest achievement in American aviation, the Collier Trophy has been awarded to Langley researchers on five occasions. The trophy, first awarded in 1911, is named for Robert J. Collier, a prominent publisher, patriot, sportsman, and aviator.



In February, 1929 this Lockheed Air Express established a new Los Angeles-to-New York nonstop record (18 hours, 13 minutes) equipped with a NACA cowl that increased the aircraft's maximum speed from 157 to 177 miles per hour. A few months later NACA won its first Collier Trophy for the cowling, the greatest achievement in American aviation in 1929.

Collier Trophies

1929	*for the low-drag engine cowling*
1946	*for de-icing research*
1947	*for supersonic flight research*
1951	*for the slotted throat transonic wind tunnel*
1954	*the transonic area rule*

Exploring NASA's Roots *was prepared by the NASA Langley Office of Public Affairs with the assistance of Dr. James R. Hansen. Dr. Hansen is the author of* ***Engineer in Charge: A History of Langley Aeronautical Laboratory, 1917-1958.***

1917 - 1992

75 Years NACA NASA

Langley
Research
Center

NASA

National Aeronautics and
Space Administration

Langley Research Center

NASA Facts

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225
(804) 864-3293

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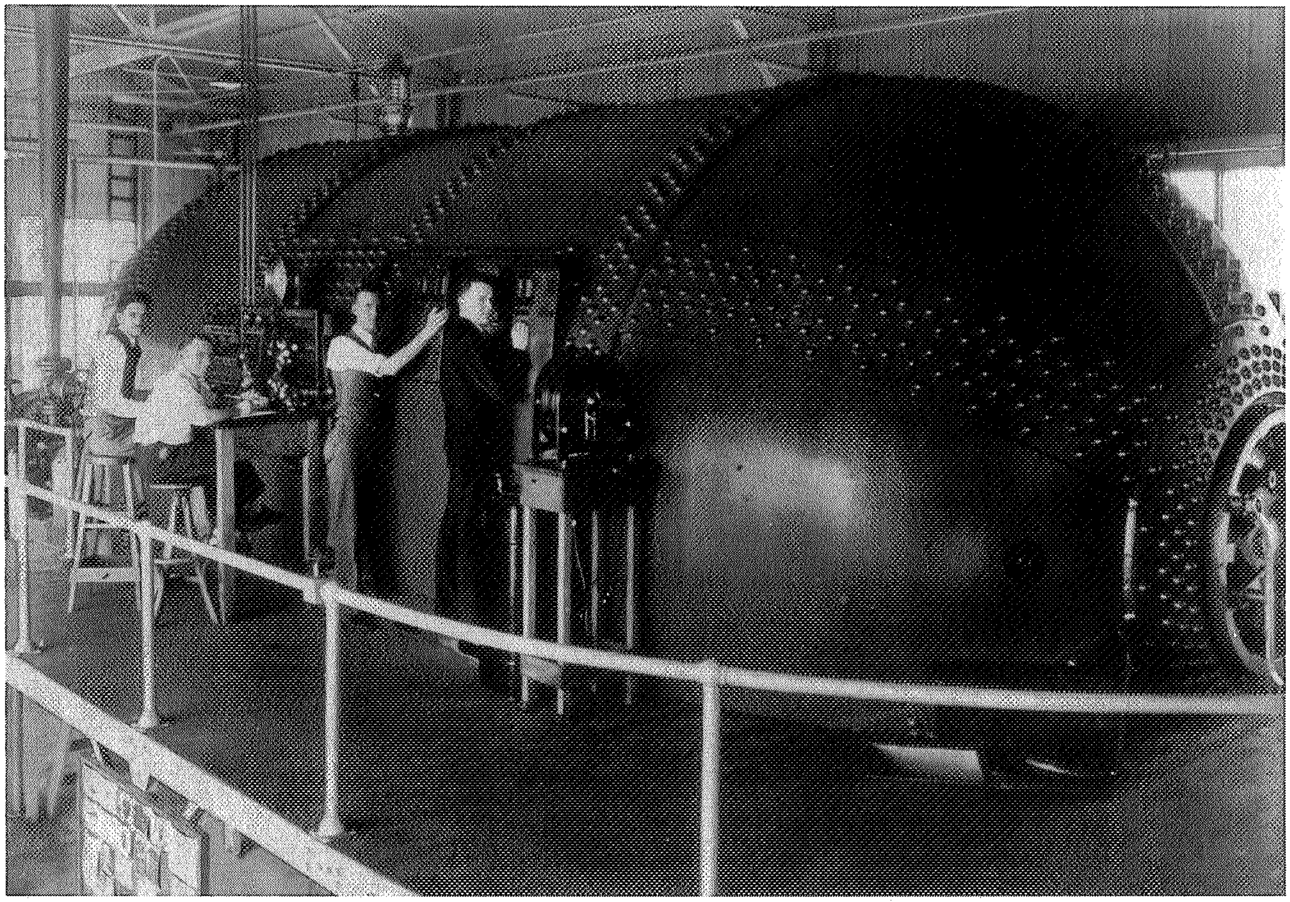
Langley Research Center
National Historic Landmarks



Eastman Jacobs (far left) and the Variable Density Tunnel (VDT) research team, March 1929. The VDT was a major contributor to the outstanding international reputation of American aeronautical research, as well as a major behind-the-scenes reason for the success of the American aircraft industry.

Few of us will ever forget where we were when Neil Armstrong first set foot on the lunar surface and made his now famous remark, "That's one small step for man; one giant leap for mankind."

It was a moment of immense pride for all Americans. And it was especially gratifying for the employees of NASA Langley Research Center, who had spent years developing and perfecting technology that helped make that first trip to the moon possible.

To honor NASA's and Langley's contribution, the United States Department of the Interior designated five Langley facilities National Historic Landmarks in 1985. They are among 26 sites nationwide so honored for inclusion in the Department's "Man in Space" project. "Man in Space" was conceived to preserve for posterity the NASA sites that most contributed to America's successful aeronautics and space programs between 1915-72, one of the most exciting periods in our nation's history.

The five Langley sites include three wind tunnels and two training facilities. The wind tunnels provided the technological base from which the early space program was initiated-they allowed us to develop the rockets necessary to take us to the moon and beyond. The training facilities were critical in preparing astronauts to actually operate in space and land on the moon.

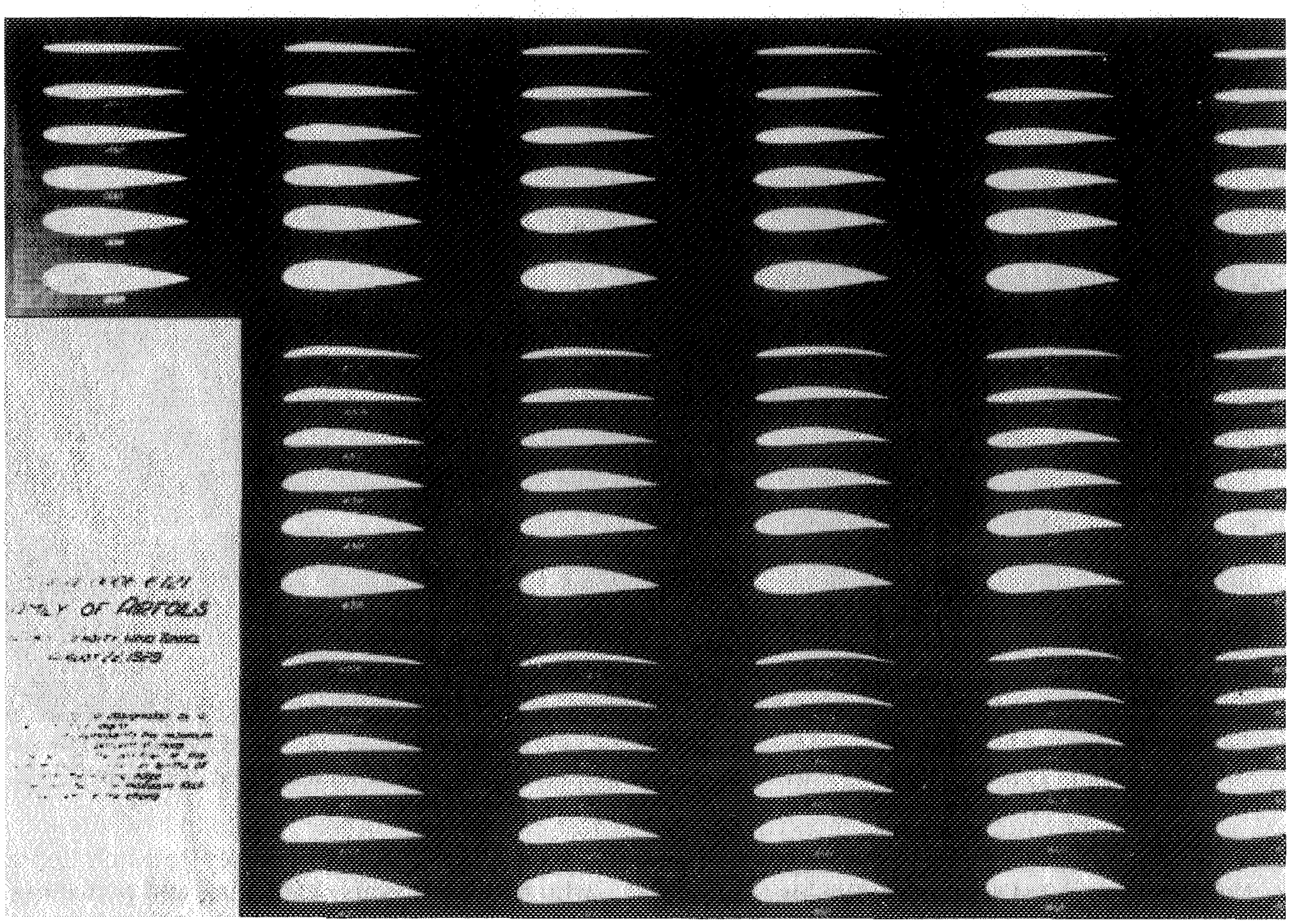
Langley's National Historic Landmarks

Variable Density Tunnel (VDT)

First operational at Langley in 1922, the VDT "put NACA on the map," according to Dick Layman, Langley's Historical Program Coordinator. The VDT was an aeronautical research tool superior to any found in the world at that time, and set an early standard for all variable density wind tunnels in use today.

Built from a design conceived by Dr. Max Munk, a German scientist familiar with European wind tunnel design, the VDT was the first pressurized wind tunnel in the world. This meant the VDT could achieve more realistic effects than any previous wind tunnel in predicting from models how actual aircraft would perform under flight conditions.

The VDT interior was destroyed by fire in 1927, but was rebuilt and placed back in service



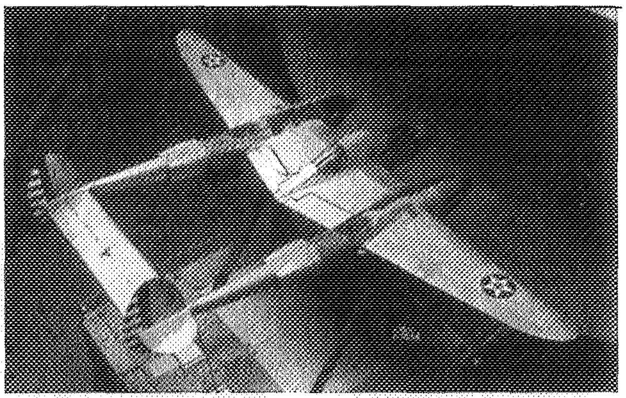
The VDT became the primary source of new aircraft wing research in the U.S. -- if not the world until the late 1930s. One of its most impressive products was a family of 78 fully tested airfoil shapes released to the aircraft industry in 1933. Many of these airfoils remain in use today. Details of this research can be found in the famous NACA technical report 460 of 1933.

in 1930. By the 1940s, however, it was obsolete and was removed from service as a wind tunnel, although its basic structure and mechanical systems remained intact.

Full-Scale Tunnel (FST)

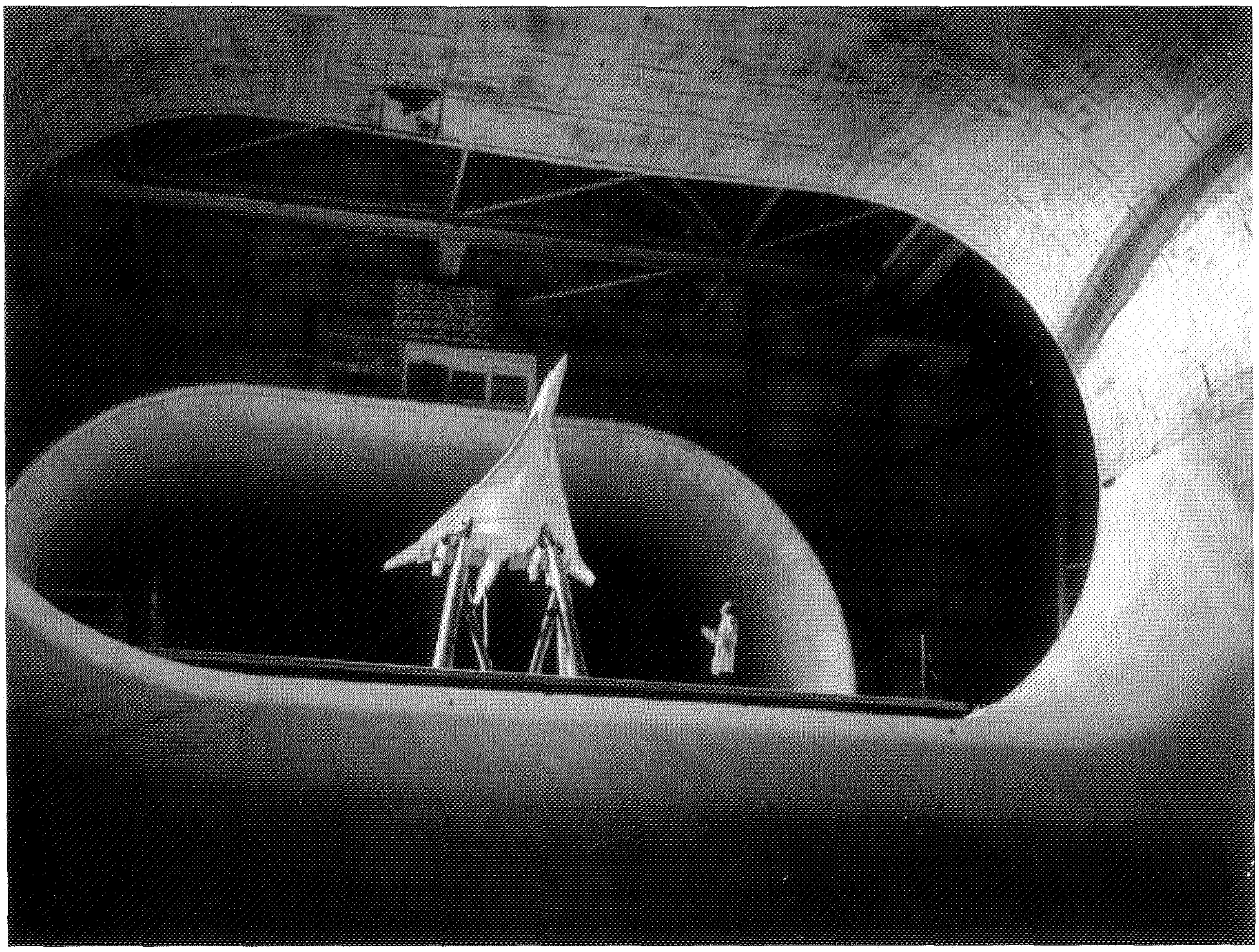
Although the VDT revolutionized wind tunnel testing concepts in the 1920s, NASA's forerunner, NACA, still needed a tunnel that could test full-scale models or actual aircraft.

In 1929 NACA began construction of the nation's--and the world's--first full-scale wind tunnel. The design team was led by Smith J. De France. The tunnel was completed in 1931. The FST was a double-return tunnel capable of moving air at speeds up to 118 miles an hour through its circuit. The tunnel was used to test virtually every high performance aircraft used by the United States in World War II. For much of the war, when it was operational 24 hours a day, seven days a week, the FST was the only tunnel in the free world large enough to perform these tests.



Drag cleanup tests were conducted on the Lockheed YP-38 Lightning in the Full-Scale Tunnel in December, 1944. Later models of the P-38 provided stellar service in World War II.

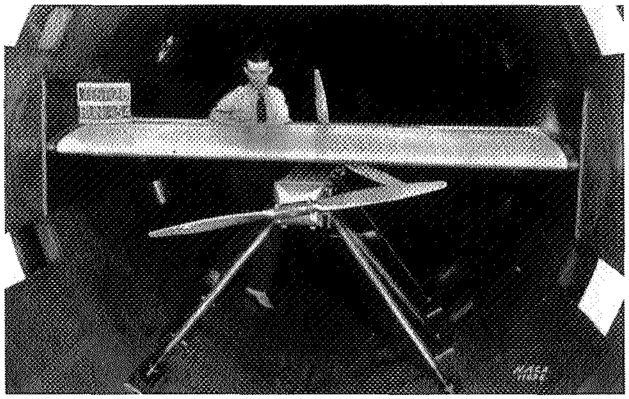
Since the war, many types of aircraft have been tested in the tunnel including the Harrier VTOL fighter, the F-16, the American supersonic transport, the Space Shuttle and Lunar Landing Test Vehicle. The tunnel is still in use today, modified to allow new testing procedures, such as free-flight and high angle of attack.



This model is one concept for a supersonic transport aircraft tested at the Full-Scale Tunnel in the early 1970s.

Eight-Foot High Speed Tunnel

This tunnel was a landmark in wind tunnel design when it was completed in 1936. It was the first continuous-flow high-speed tunnel. This meant it could operate almost indefinitely to produce a high-speed airstream approaching the speed of sound. And it was large enough to accommodate large scale models, and even actual aircraft sections.

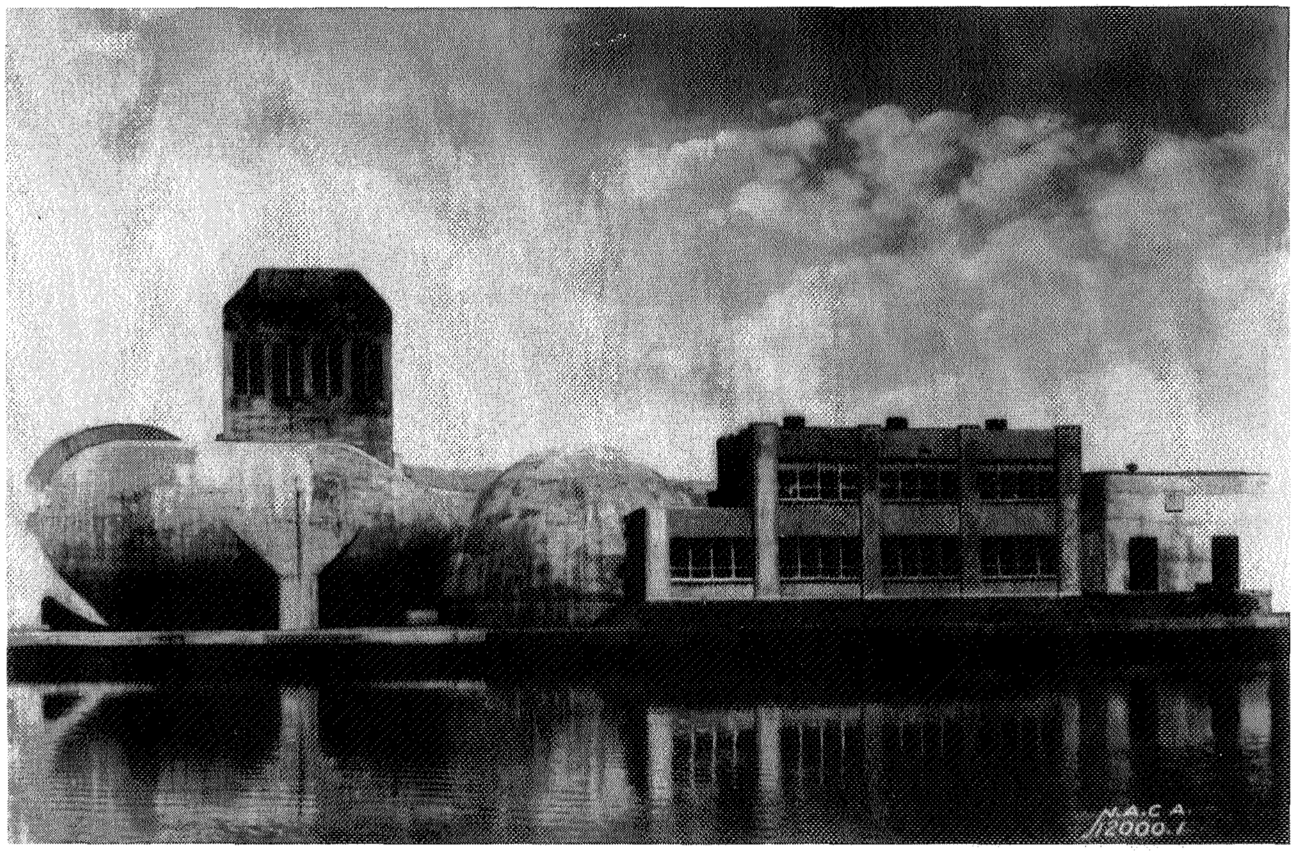


The windmill power of an experimental propeller is tested in the 8-Foot HST in May 1939. This tunnel produced the high-speed cowling shapes used in World War II aircraft, and a new family of efficient air inlets used in early jet aircraft. Its greatest achievement was the development and operational demonstration of the first transonic slotted throat wind tunnel.

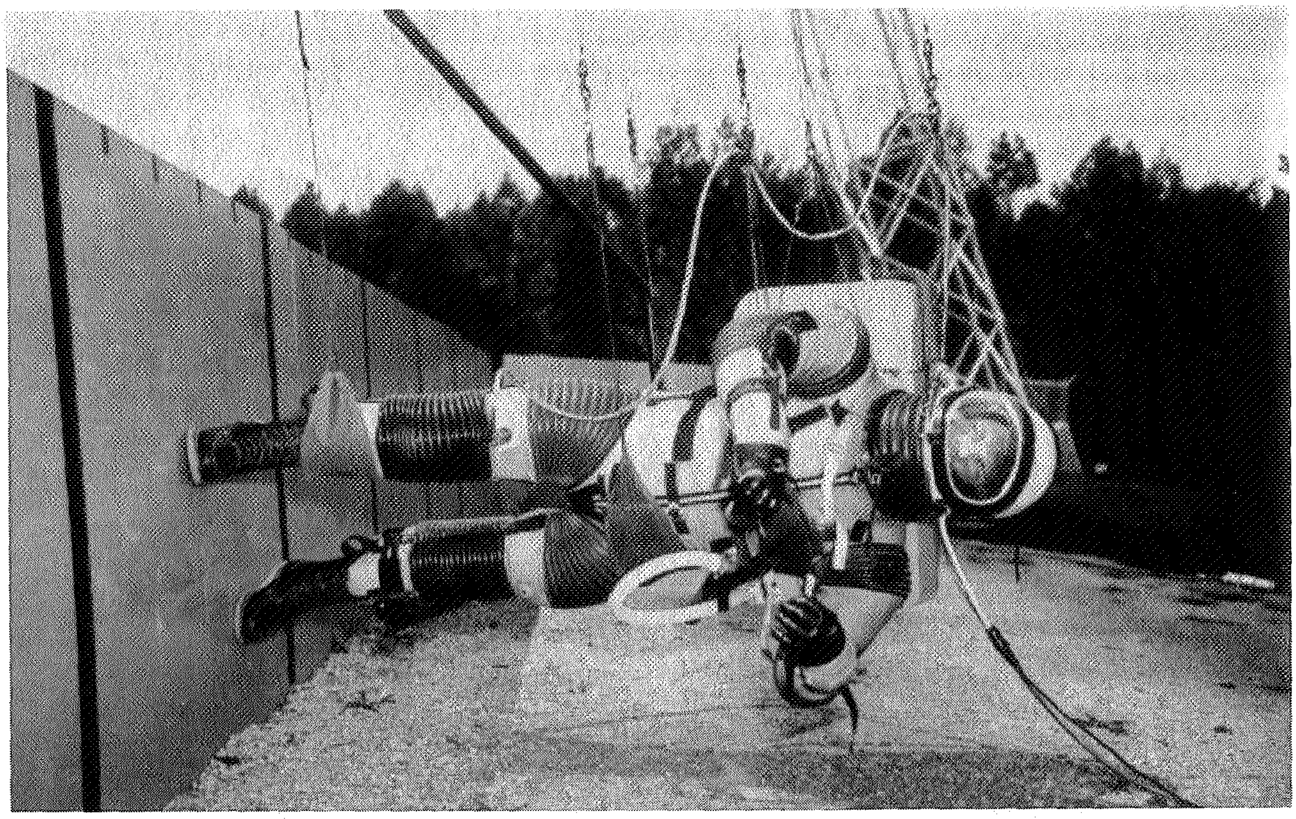
In 1950, the tunnel was the first in the world to be modified to incorporate a slotted throat design. This revolutionary design gave researchers their first accurate data on airframe performance in the transonic range. The tunnel was deactivated in 1956, when a new 8-foot pressure tunnel was built near it.

Lunar Landing Research Facility

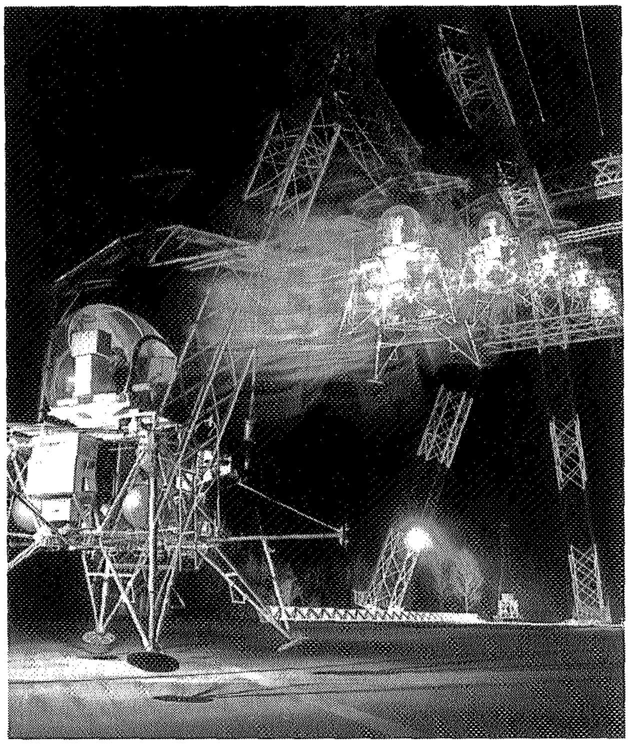
This essential facility allowed NASA to train Apollo astronauts to fly in a simulated lunar environment. Neil Armstrong, Edwin Aldrin and 22 other astronauts used the facility to practice piloting problems they would encounter in the last 150 feet of descent to the surface of the moon. It was built in 1965 and was basically an A-frame structure with a gantry used to manipulate a full-scale Lunar Excursion Module Simulator (LEMS).



The concrete walls of the igloo-like structure around the test section of the 8-Foot High Speed Tunnel were one foot thick. The tunnel was used to study models of aircraft and aircraft components in a high-speed airstream approaching the speed of sound.



Ingenious lunar-gravity simulator. A suited astronaut is cable-supported so that one-sixth of his weight is applied to an inclined wall to simulate walking on the surface of the moon.



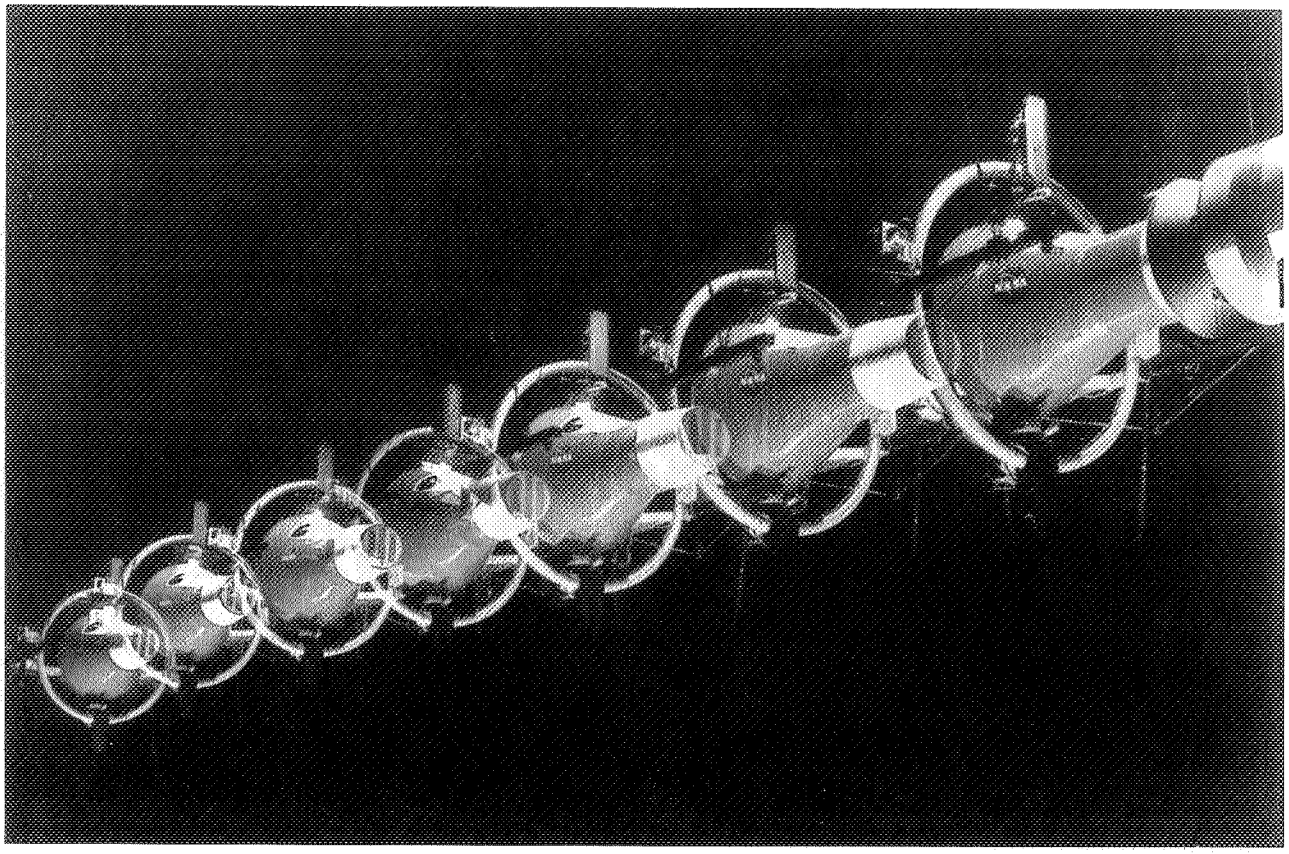
Multiple-exposure shows how most forward motion was cancelled during descent of Apollo's Lunar Excursion Module Simulator (LEMS). The vehicle was designed at Langley Research Center.

The astronauts were also able to practice walking on a simulated lunar surface, as the base of the Lunar Landing Research Facility was modeled with fill material to imitate the moon's surface. Suspended by slings and cables on their sides, the men experienced what it would be like to walk on the moon where gravity is only 1/6 of that on Earth.

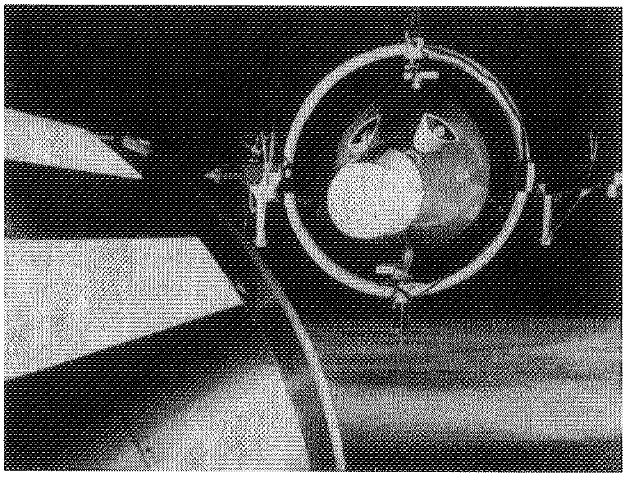
Today this facility is used for aircraft impact dynamics studies. The lunar landscape has been replaced by an impact runway that can be modified to simulate different crash environments. The LEMS has also been refurbished, and the names of many of the astronauts who trained at the Lunar Landing Research Facility are listed on its exterior. Today, the LEMS is on exhibit at the Virginia Air and Space Center in Hampton.

Rendezvous Docking Simulator

Built in 1963, this full-scale simulator was used by Gemini and Apollo astronauts to practice pilot-controlled rendezvous and docking techniques needed to link two vehicles in space. As man's first trip to the moon was accomplished using two spacecraft--a moon-landing vehicle that could boost itself back into lunar orbit to link up



What may appear to be a fleet of spacecraft flying in formation is actually a multiple exposure of the Rendezvous Docking Simulator with a Gemini spacecraft mockup attached at right.



Two research pilots simulate Earth orbit rendezvous and docking in a full-scale mockup of the Gemini spacecraft. The rendezvous docking simulator enabled researchers to determine an astronaut's ability to complete a rendezvous in either Earth or lunar orbit.

with the Command Module--this docking technique was critical to the success of the entire mission.

The simulator consists of an overhead carriage and cable-suspended gimbal system. Full-scale modules of both the Gemini and Apollo spacecraft could be hung from the simulator allowing pilots to "fly" the vehicle to practice docking with other spacecraft.

After the completion of the Apollo program, the simulator was modified for other purposes and its Apollo Command Module was replaced by an aircraft cockpit. It is no longer in use today.

Facts and Figures

Variable Density Tunnel

Operational:	*1922*
Initial Cost:	*$262,000*
Designer:	*Dr. Max Munk, a NACA scientist/engineer from Germany*
Circuit and Pressure:	*Continuous, annular return; 20 atmospheres*
Test Section:	*5′ diameter, closed throat*
Drive System:	*Fan; 250-HP electric motor*
Maximum Speed:	*51 MPH*
Status:	*Inactive*

Full-Scale Tunnel

Operational:	*1931*
Initial Cost:	*$900,000*
Designer:	*Smith J. De France*
Circuit and Pressure:	*Double return, atmospheric Test Section: 30′ by 60′, open throat (capable of testing aircraft with spans of 40 feet)*
Drive system:	*Two fans; two 4000-HP electric motors*
Maximum Speed:	*118 MPH*
Status:	*Still operational*

Lunar Landing Research Facility

Operational:	*1965*
Initial Cost:	*$3.5 million*
Structure:	*400′ x 230′ A-frame steel structure*
Status:	*Currently used to test structural design of aircraft to resist impact during crashes*

The Lunar Excursion Module Simulator was used for training in conjunction with the Lunar Landing Research Facility.

Weight:	*12,000 pounds*
Cab Size:	*Could accommodate two astronauts with a common instrument panel mounted between them*
Status:	*Inactive. Refurbished and on display at the Virginia Air and Space Center in Hampton*

Rendezvous Docking Simulator

Operational:	*1963*
Structure:	*Overhead carriage and cable-suspended gimbal system. Could accommodate full-scale models of the Gemini and Apollo spacecraft*
Status:	*Inactive*

Eight-Foot High-Speed Tunnel

Operational:	*1936*
Initial Cost:	*$266,000*
Circuit and Pressure:	*Single return, atmospheric*
Test Section:	*8′ diameter, closed throat*
Drive System:	*Fan; 8000-HP electric motor*
Maximum Speed:	*575 MPH (Mach 0.75)*
Major Modifications:	*Repowered to 16,000 HP (mach 1 capability) in 1945; Mach 1.2 contoured nozzle installed in 1947; slotted-throat test section installed in 1950.*
Status:	*Deactivated in 1956*

Langley Research Center National Historic Landmarks** was prepared by the NASA Langley Office of Public Affairs with the assistance of Dr. James R. Hansen. Dr. Hansen is the author of **Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958.

1917 - 1992
75 Years
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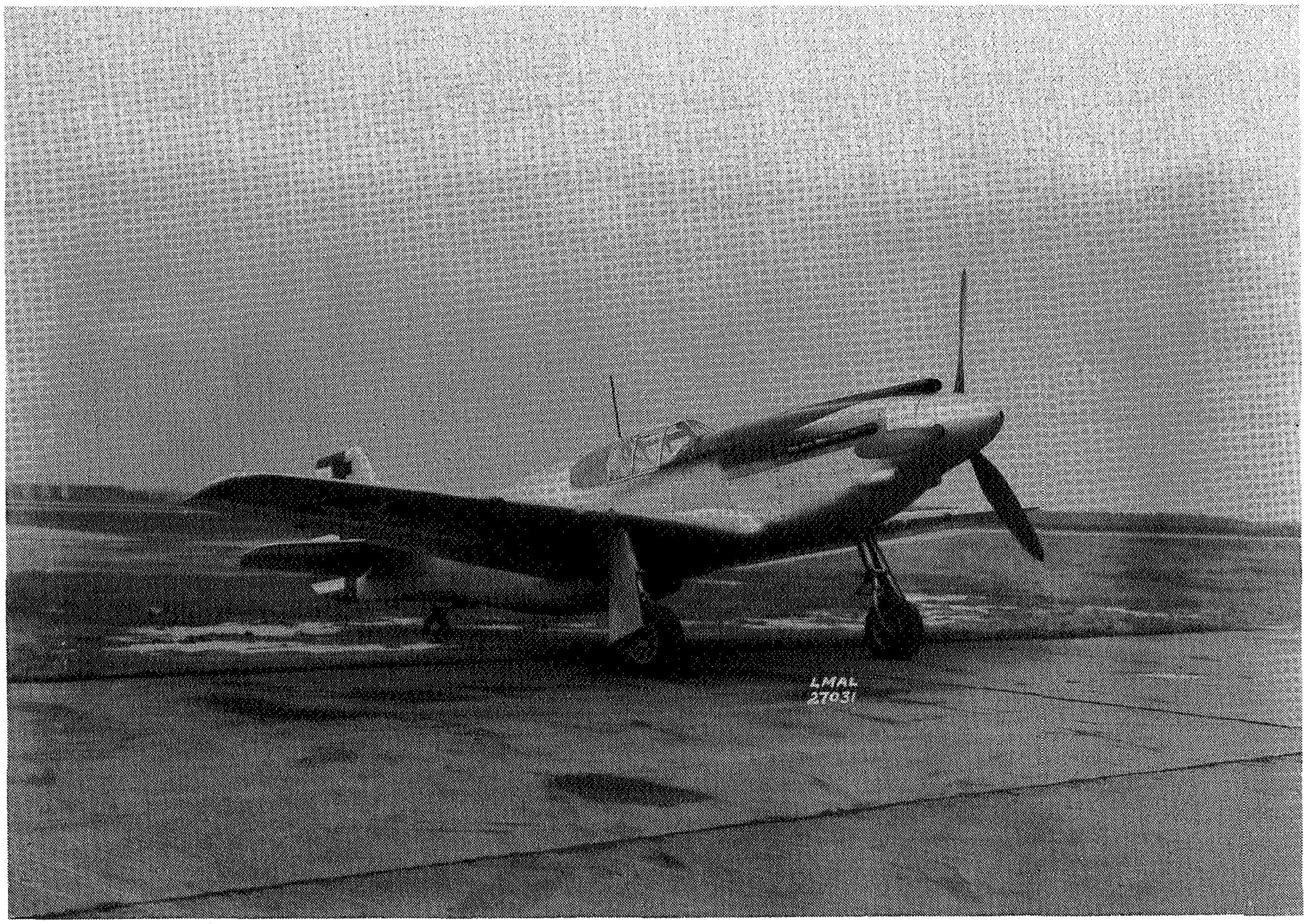
NF171-April 1992

The Mustang Story: Recollections of the XP-51

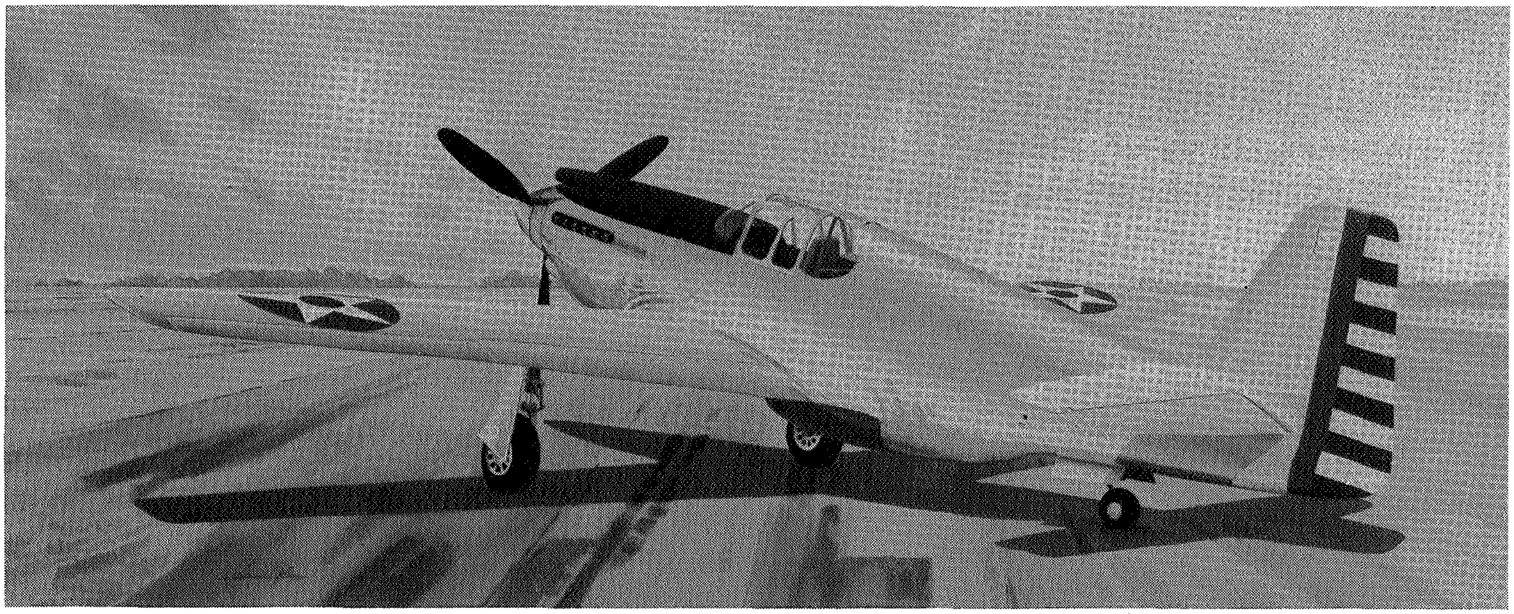
By John P. Reeder NACA/NASA Test Pilot



Beginning in 1940, Langley helped North American Aviation test its prototype of the P-51 Mustang, the first aircraft to employ the NACA laminar-flow airfoil in the wing design. The aircraft was used in all theaters of operation during World War II. And about 15,000 of the series were constructed. During the war the plane represented the highest level of technical refinement ever achieved in a propeller-driven fighter aircraft. Built as the fourth North American XP-51 Mustang, this plane arrived at Langley for NACA trials in December 1941.

Reprinted from *Sport Aviation* Magazine, September 1983 Edition

The Mustang Story:



Last summer during Oshkosh '82, EAA President Paul Poberezny piloted XP-51, Serial Number 41-38, on its last flight. Subsequently, the sleek little fighter has been put on display in the EAA Foundation's new Aviation Center as the centerpiece of the Warbird section.

Developed in 1940 by North American for the British, the handmade prototype of the Mustang was so successful that the design was quickly committed to production . . . with the fourth production machine going to Wright Field for evaluation by the U.S. Army Air Corps. This aircraft, Ser. No. 41-38, was later turned over to NACA and spent most of World War II serving as a test bed for a number of aeronautical experiments. After the war, it became a part of the National Air and Space Museum's collection, and in 1975 was traded to the EAA Foundation for a Northrop Alpha. That August, the XP-51 was trucked to Ft. Collins, CO where it spent the next year undergoing a complete restoration by Darrell Skurich. The Allison engine was overhauled by John Sandberg's METMA in Minneapolis.

Darrell flew the resurrected fighter, now resplendent in a new Charles Day paint job, to Oshkosh '76 for its debut into the world of sport aviation. It was maintained in flying condition . . . although rarely flown other than during the annual EAA Conventions . . . until its retirement last summer.

As the earliest existing P-51 and the very first to be delivered to the U.S. government, the airplane is a very significant artifact. It is the nearest thing we have today to the progenitor of the entire legendary Mustang line . . . and as you will read in the following article, was the airplane that opened the Air Corps' eyes to the design's potential.

As mentioned, Ser. No. 41-38's operational days were spent in a research and developmental role. One of the pilots who flew it was "Jack" Reeder, who recently retired from a long and distinguished career with NACA/NASA. Several years ago, he promised that one day he would write up his recollections of the XP-51 . . . which he has now done.

WAR WAS UNDERWAY in Europe and the British and French were in desperate need of more fighter aircraft, particularly for reconnaissance and support of ground forces. When a British Air Purchasing Commission arrived in the U.S. in April 1940 to arrange for procurement of additional aircraft, it considered only two U.S. fighter aircraft eligible, although not ideal. These were the Curtiss P-40 and the Bell P-39. These would require some modifications to accommodate some of the lessons of the war up to that time (before the Battle of Britain). After the British had contracted for P-40's and P-39's within the constraints of the companies' production capacity, they asked the North American Aviation Co. (NAA) in Los Angeles to consider production of P-40's also. Discussions indicated that about 120 days would be required to tool up and set up the production lines at NAA. NAA officials suggested to the British that, within 120 days, a completely new and better airplane could be designed and built specifically to British requirements and would be better adapted to mass production. British requirements included higher speed and rate of climb, improved maneuverability up to higher speeds, and increased range and firepower compared with current fighters. The British approved a preliminary design by NAA on May 4, 1940, and were impressed enough to order 320 of this NAA design, NA-73, on May 29, 1940. The airframe was complete on September 9, 1940, having required 2800 drawings and 60,000 man hours, but the priority for the only engine available at that time, the Allison V-1710-39 of 1150 hp, had not been high enough within that company's limited production capacity to avoid a delay. As a result, the first flight, highly successful, was not made until October 26, 1940. Although some aerodynamic corrective changes were required, the aircraft proved to be a masterpiece of advanced, integrated aerodynamic design, an example of intelligent application of government research and industry information available. It was also a handsome airplane. It was the first airplane to use the laminar flow airfoil concept of the National Advisory Committee for Aeronautics (NACA) in the wing design. However, laminar flow with its low skin friction drag was not realized because the required wing surface smoothness could not be obtained on the production line nor preserved in service. However, the shape of the laminar flow airfoil reduced peak airflow velocities over the wing, thus postponing and minimizing "compressibility" effects on the airplane (drag rise, lift loss, nose down "tuck", buffeting and loss of elevator effectiveness for dive recovery) which plagued other contemporary fighters above a Mach number of about 0.7. The new airfoil thus gave the P-51's an advantage in high speed combat encounters.

By John P. Reeder (EAA 105751)

NACA/NASA (Ret.)

247 James River Drive

Newport News, Virginia 23601

The overall handling characteristics of the XP-51's (Mustang I's) were nearly ideal, particularly when compared with other fighters of the period. Later P-51 models, as a result of the effects of increased power (larger crosswind forces on the propeller due to angle of attack and sideslip and more intense slipstream rotation effects at the tail) and configuration changes, suffered some deterioration in stability and control characteristics. This resulted in corrective modifications, such as added tail surface area (and tail length in the case of the P-51H), and bob weights to increase elevator force feel in maneuvers.

The official top speed in level flight of the early production model (Mustang I, or U.S. Army Air Corps XP-51) was 382 mph at 13,700 feet altitude, the critical altitude of this low altitude engine. As an example of how advanced this aircraft was, consider the case of a long established U.S. fighter designer and builder who also had access to the same research and development information as NAA did. Starting on an advanced fighter in the same year the Mustang I was conceived, this company delivered its new fighter, powered by the same Allison engine as the XP-51, to the AAC in 1942, the year following the XP-51. It was smaller and lighter than the XP-51, but achieved only 355 mph top speed, 27 mph slower than the Mustang I. As a matter of fact, the Mustang I was about 30 mph faster than nearly all contemporary fighters, including the Spitfire. This company's next version of an advanced fighter, using the same high altitude Merlin engine as the P-51B, was delivered in 1943 and was 50 mph slower than the P-51B. The P-51 came into its own when it was re-powered with Rolls Royce Merlin high altitude engines, the V-1650-3 and V-1650-7. These engines were by this time being built by Packard in the U.S. The P-51B, entering combat operations in 1943, and the P-51D, which entered combat operations in 1944, maintained a speed margin over all other allied fighters in production until mid-1944. The last production model of this aircraft, the P-51H, was too late to see service in Europe but limited numbers served in the Pacific as escorts for B-29 bomber operations against Japan. It was the fastest propeller-driven fighter in the war, at 487 mph.

Most significantly, the superior range of the P-51's was due to their aerodynamically efficient design and large internal fuel capacity, augmented with large external drop tanks, which allowed up to 7½ hour missions. This allowed protective escort of the heavy bombers to the heart of Germany for the first time, which was an important key to victory in Europe. As a fighter, the P-51's destroyed 4,950 enemy aircraft in combat and 4,131 on the ground in the European theater alone. It was very successful in the Mediterranean and Pacific theaters as well, having performed all the roles of a fighter in outstanding fashion.

The Story of XP-51 #41-38

When the U.S. Government, in 1940, gave the British Air Purchasing Commission permission to deal directly with NAA in creation of a new fighter aircraft, it directed that two copies of the first production lot of the new aircraft be provided the U.S. Army Air Corps (USAAC) for evaluation at no cost, a routine procedure for aircraft designed and built in the U.S. for foreign governments. Consequently, the numbers 4 (USAAC number 41-038, 1038, or 41-38) and 10 (number 41-39) NA-73 (Mustang I) production aircraft were delivered to the AAC at Wright Field, Ohio, in August and December 1941, respectively. They were, at this time, designated XP-51's. They were delivered in their natural aluminum finish with the blue bar and red and white stripes on the rudder (see Figure 1), and the red, white and blue star insignia on top and bottom of the wing.

Little enthusiasm was shown for the XP-41 #41-38 at Wright Field when delivered. In September a new pneumatic gun charger, of interest to both the U.S. and the British, was installed in the XP-51, since it was not otherwise scheduled, and evaluated at Eglin Field in Florida. The world soon came back that the XP-51 was the best fighter

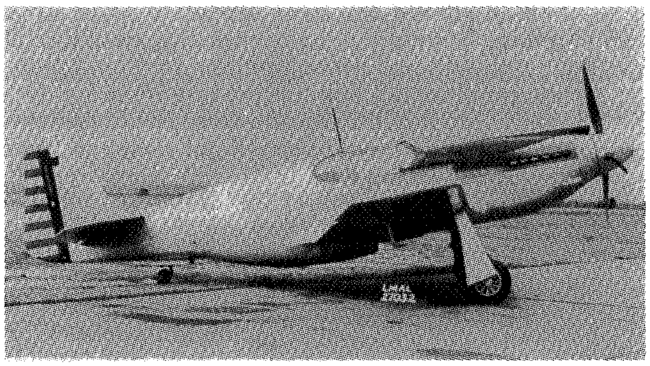


FIGURE 1 - XP-51 #41-38 as delivered to NACA Langley in Dec. 1941.

in the Army inventory. Evaluation and acceptance tests were subsequently completed at Wright Field in October. In December 1941, the XP-51 #41-38 was assigned to the National Advisory Committee for Aeronautics (NACA), an independent government research agency, at its laboratory at Langley Field near Hampton, VA. The NACA, forerunner of NASA, was established by the U.S. government in 1915 "... to supervise and direct the scientific study of the problems of flight, with a view to their practical solution ..." One of the endeavors of the NACA Langley laboratory in the mid-thirties was to explore, measure with specialized instrumentation and evaluate with trained research pilots the many individual characteristics that make up the handling and flying qualities of aircraft. The objective was to quantify the many significant characteristics as criteria for use in design of new aircraft, and as a standard for acceptance or certification of operational aircraft. Following the methodical and detailed evaluation of over 20 aircraft of all types, a classified report was published by Gilruth in April 1941 entitled "Requirements for Satisfactory Flying Qualities of Airplanes." This report was to become the cornerstone for military handling qualities requirements, first established by the Army in 1943, as well as for civil aircraft certification requirements. The U.S. Army, supportive of the NACA work, assigned the XP-51 #41-38 to NACA Langley on loan for corroboration and possible upgrading of the NACA recommended requirements. NACA evaluation and measurements showed that the XP-51 easily satisfied all the proposed requirements, except for rolling velocity capability. This XP-51 aircraft was to prove, in general, an example of good handling qualities for years to come. Figure 2 shows a group of NACA pilots in front of XP-51 #41-38 in 1943. The author is on the reader's left.

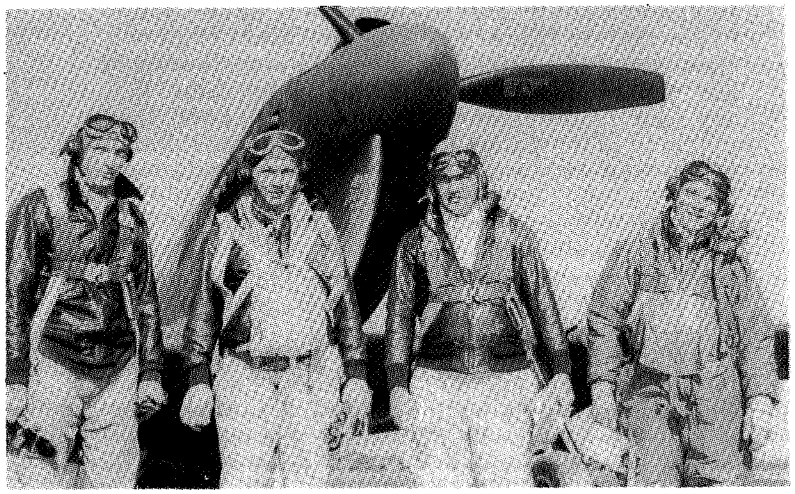


FIGURE 2 - Group of NACA pilots in front of XP-51 #41-38 in 1943. Author is on viewer's left.

With regard to roll control, the British Air Purchasing Commission had specified a single requirement for the NA-73. The aircraft was to generate a wing tip helix angle (similar to the pitch of a propeller) of 0.04 radian while rolling at 400 mph indicated airspeed without exceeding a stick force of 50 pounds. To help achieve this, NAA had provided a high mechanical advantage, to keep the stick forces down, by limiting the aileron deflection to ± 10° and providing ± 9 inches of stick throw (± 7 inches was later to be the U.S. Air Force specified limit). Geared balancing tabs were added after early flight tests in order to further reduce stick forces. However, the measured roll rate at 400 mph with 50 pounds stick force was only 75% of that specified by the British, but it was comparable to other contemporary fighters at this speed. Also, the achievable roll rate at lower speeds was far lower than other contemporary fighters. A comparison of measured roll capability of several prominent WW II fighters, including the XP-51, is shown in the accompanying chart, Figure 3.

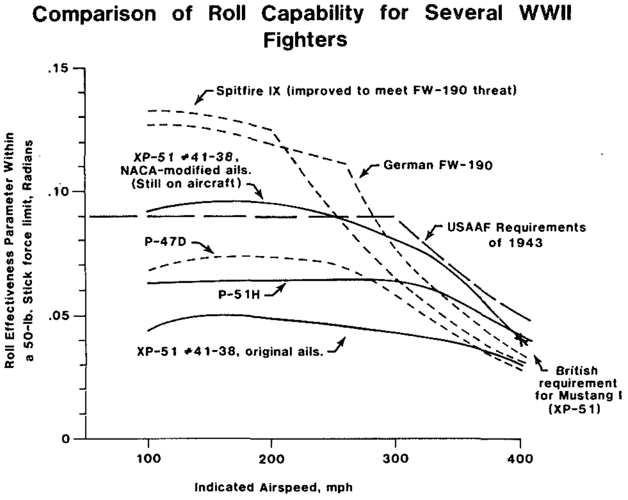


FIGURE 3.

The NACA, recognizing the deficiency in roll control in its report, undertook, at the request of the Army, to improve roll effectiveness within the 50 pound stick force limit, although NACA considered a 30 pound limit more reasonable. (The current AF stick force limit is 20 pounds for roll.) Maximum deflection of the ailerons was doubled to ± 20° by NACA and the stick forces reduced by thickening and "bevelling" the trailing edges of the ailerons (see Figure 4) which produced "balancing" pressure changes

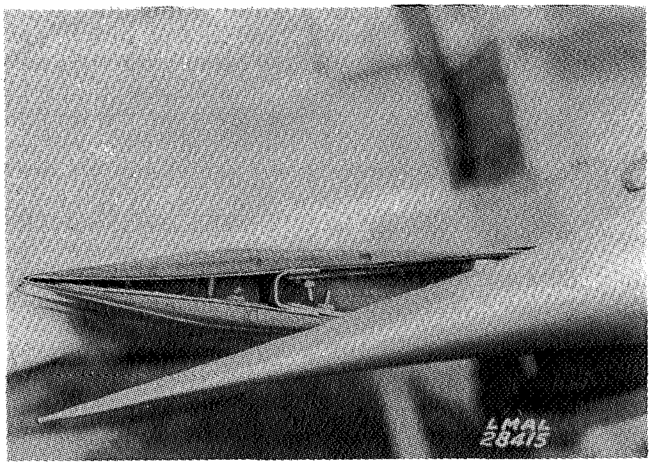


FIGURE 4 - End view of modified right aileron on XP-51 #41-38, showing "bevelled" surfaces overlaying the original "cusped" aileron.

over the surfaces. Also, geared "balancing" tabs were retained. Measured roll rates were significantly increased throughout the speed range due to the increased aileron deflection used, and the early British specifications at 400 mph indicated airspeed was met, as shown in the comparison of contemporary fighters in Figure 3. The roll capability called for in the first AAF specification for flying qualities published in 1943 is also shown on the chart. These NACA-modified one-of-a-kind ailerons, developed in 1942-1943, remain on the XP-51 #41-38 to this day. Although the chart shows the relative roll capability of the several fighters quite well, it does not show rate of roll, which is a function of wing span, and of true airspeed with a given stick force. For roll rate comparison, consider a dog fight at low altitude with a maneuvering speed of 225 mph indicated airspeed. Both the improved Spitfire and FW-190 could roll at about 126° per second, the modified XP-51 #41-38 at 95° per second, the P-47D at 69° per second, the P-51H at 65° per second and the original XP-51 at 48° per second. Should the combat occur at 350 mph indicated airspeed at 20,000 feet altitude (468 mph true airspeed) the situation with regard to roll capability will have changed. The roll rate for a given aileron deflection is in direct proportion to true airspeed, but the aileron deflection obtainable would be limited to that at which the assumed stick force limit of 50 pounds is reached. Therefore, in this 350 mph indicated speed case, the XP-51 #41-38 with the modified ailerons would have the highest roll rate capability of 138° per second, the FW-190 second with 119° per second, the P-51H a close third with 117° per second, the Spitfire IX next with 110° per second, and the P-47D and the XP-51 with the original ailerons would be a poor fifth and sixth, with 81° and 80° per second, respectively. Thus, speed, as it affected roll performance, was an important aspect of combat.

Recent research results using jet fighters found that pilots seldom exceeded 100° per second rate of roll in the acquisition and tracking of a maneuvering target, even though higher rates were available, in order to avoid disorientation. However, excess aileron was used to advantage for increased angular acceleration in initiating rolling maneuvers, or in evasive action.

During 1942, midway through the aileron development program at NACA, the aircraft was refinished in a dull olive drab color in compliance with an Army Air Forces Technical Order. This followed the organizational change from Army Air Corps to Army Air Forces. Thus, olive drab was the color of the aircraft when acquired by the EAA.

The P-51B and later production models had increased aileron deflections of ±15° and employed a different aerodynamic means of reducing (or balancing) the aileron stick forces than NACA used. However, these models, as shown by the P-51H data in Figure 3, as well as other U.S. Fighters of the era, did not meet the 1943 Air Forces specifications.

As a NACA research pilot, I eventually had the opportunity to fly 40 different fighters, 22 of which were propeller- driven. These included the XP-51, P-51B, P-51D, P-51H and the XP-82 and P-82B. The P-51's were my favorite fighters. They were fast, simple and easy to fly, had long range and were designed for pilots. I first flew the XP-51 #41-38 in early 1944, after completion of its aileron development program. At that time I had had previous experience with 9 different fighters, including the P-51B. I made some 43 high speed research flights in the XP-51 for various aerodynamic investigations. It was one of the most pleasant and exciting propeller-driven planes I have flown. It had nearly ideal handling qualities, and for the experienced pilot it had no vices. It had a desirable degree of static and dynamic stability about all axes, light but positive control forces, and it responded quickly and accurately to pilot control inputs. Trim changes with power, flaps and speed were small with low control force changes. At diving speeds, "compressibility" trim changes and buffeting were relatively mild and recovery from high speed dives with longitudinal control alone was readily accomplished, although we at NACA developed and evaluated dive recovery flaps for this airplane. The modified ailerons of this aircraft were pleasantly light and responsive. Take-off, landing and ground handling characteristics were very good for a tail sitter, with the exception of the limited forward visibility with the tail down. Crash helmets could not have been worn in the restricted confines of the "birdcage" canopy. Head movement and visibility were more restricted than for the P-40, as an example. There was no air conditioning in those days and ventilation was limited — it was a "sweat box" at low altitude. Cabin pressurization was also unknown in those days, so ears could suffer in a dive if one had a cold or sinus problem.

In 1943 the XP-51 #41-38's sister ship, #41-39, shown in Figure 5 in its olive drab finish, was assigned to NACA Langley for a systematic, scientific study of high speed

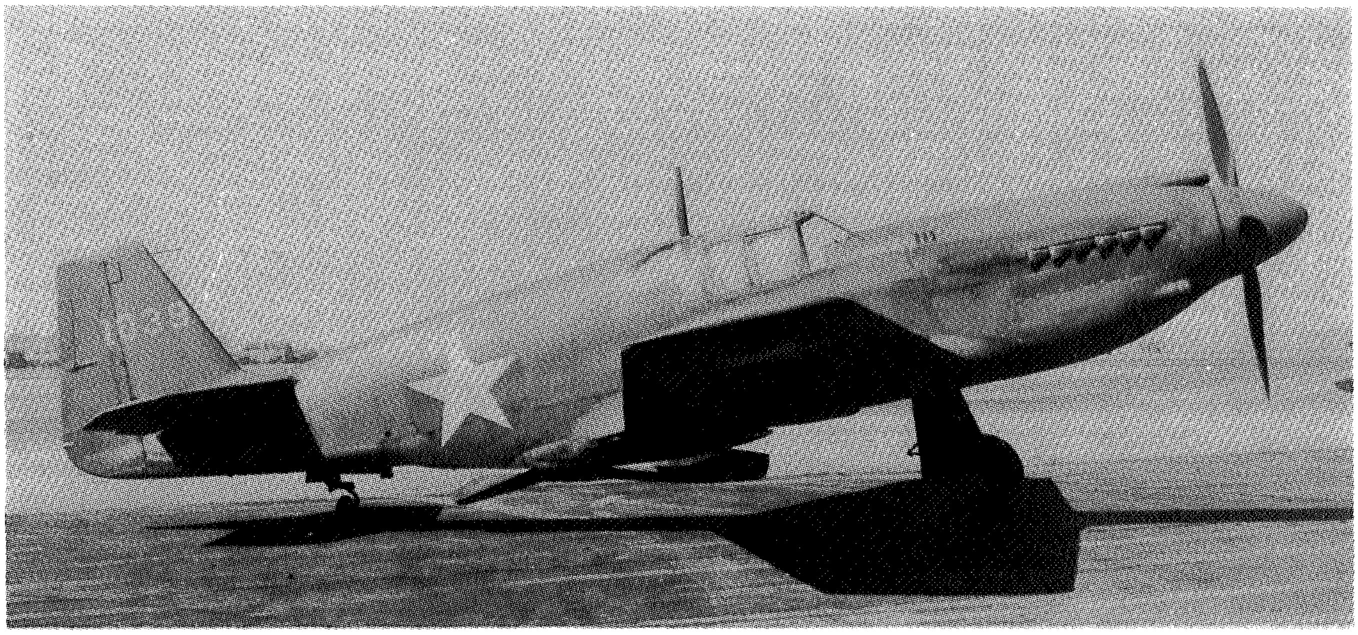


FIGURE 5 - XP-51 #41-39 as delivered to NACA Langley in March 1943. Note olive drab finish, and open cooling duct doors at inlet and exit. Later P-51's had fixed geometry inlet.

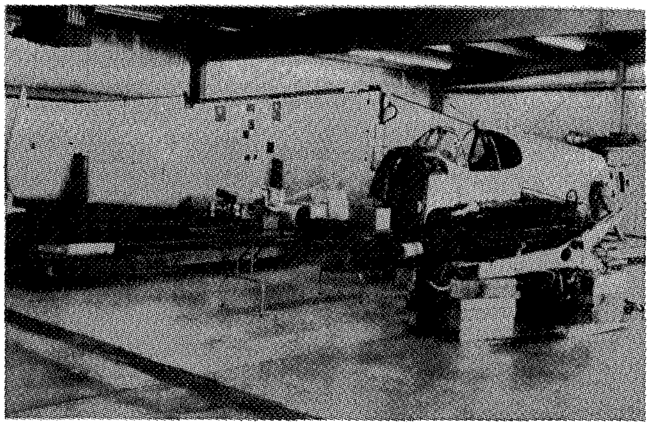
"compressibility" effects. This aircraft had the original ailerons. When I had a chance to fly this aircraft, I was surprised at how low the roll response was compared with other aircraft, including the #41-38. During a landing approach on one windy and gusty day in this aircraft, I found myself concerned with keeping it under adequate lateral control for a safe landing.

One of my early thrills in the SP-51 #41-38 was flying at low altitude for an airspeed calibration. In the technique used in this case, the airspeed static pressure source was calibrated by flying past a known reference station above ground level at a succession of increasing steady airspeeds up to maximum. The static pressure in terms of altitude was read by the pilot in the cockpit on a large sensitive altimeter supported on shock cord above the instrument panel. An observer at the reference station noted similar altimeter readings, made observations of airplane height errors, and took camera pictures simultaneously with airplane passage. This station was a platform on top of the old dirigible hangar at Langley Field, a height of about 110 feet. Static pressure error, and corresponding airspeed error, could thus be derived. The thrill for the pilot came from the traverse of this low altitude pattern over the countryside at speeds up to 310 mph while establishing and maintaining the desired incremental speeds past the reference station.

One incident I remember with this airplane was a blowout of the left tire during a take-off roll after the tail had come up. I elected to abort, which I did satisfactorily, using moderate braking for directional control. There was no damage to the aircraft.

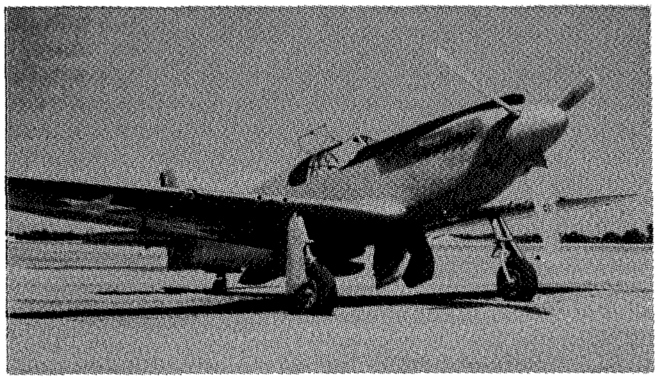
At the end of NACA research with the XP-51 #41-38, it was returned to the AAF. It was ferried from Langley Field to Seymour Field in Freeman, Indiana, on July 25, 1945, ostensibly to be used as a static exhibit for an Armed Forces Day show. It eventually ended up in the Silver Hill Storage Facility of the National Air and Space Museum. It was later traded to EAA for the Northrop Alpha now on display at the NASM in Washington.

The XP-51 #41-38, now in the EAA Aviation Center, is a very significant aircraft, as well as a pleasant airplane to fly! It was number 4 from the first production lot of the British Mustang I fighter of WW II, one of the first of a famous lineage of 15,582 P-51 fighters which were to dominate the skies over Europe. Born of the war in Europe, the aircraft was the brainchild of a courageous, enterprising and competent company which accelerated the application of advanced technology to airplane design. Its features reflect sound aerodynamics. Its significance to the war effort can best be appreciated by the comment allegedly made by General Goering of the German Air Force when he saw P-51's accompanying the heavy bombers over Berlin: "The war is over."



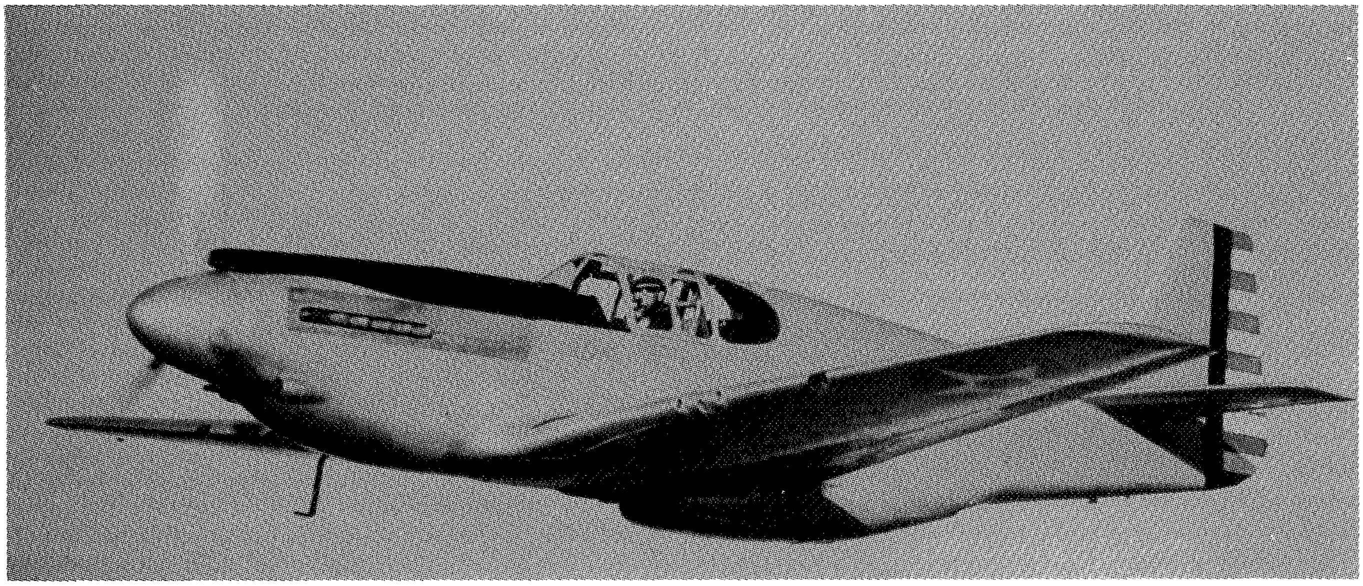
(Photo by Lee Fray)

The XP-51 in the summer of 1975, shortly before being trucked to Darrell Skurich's shop in Ft. Collins, CO for restoration. EAA had received the fighter from the NASM in crates. It was removed from them and stripped of its OD paint before shipment to Colorado.



(Photo by Dick Stouffer)

The restored XP-51 at Oshkosh in 1978.



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Years
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Langley Research Center
Hampton, Virginia 23665-5225
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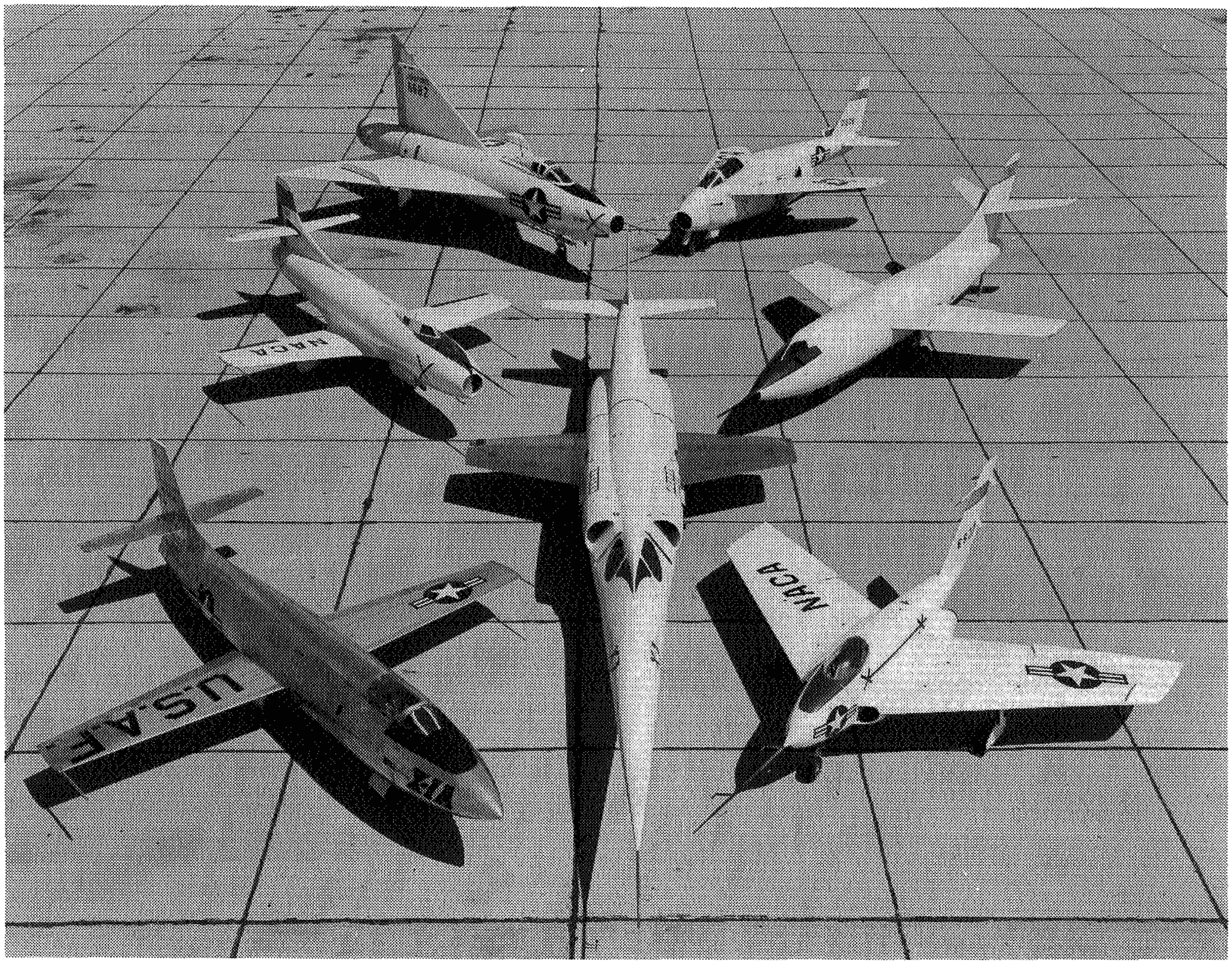
NF166 – January 1992

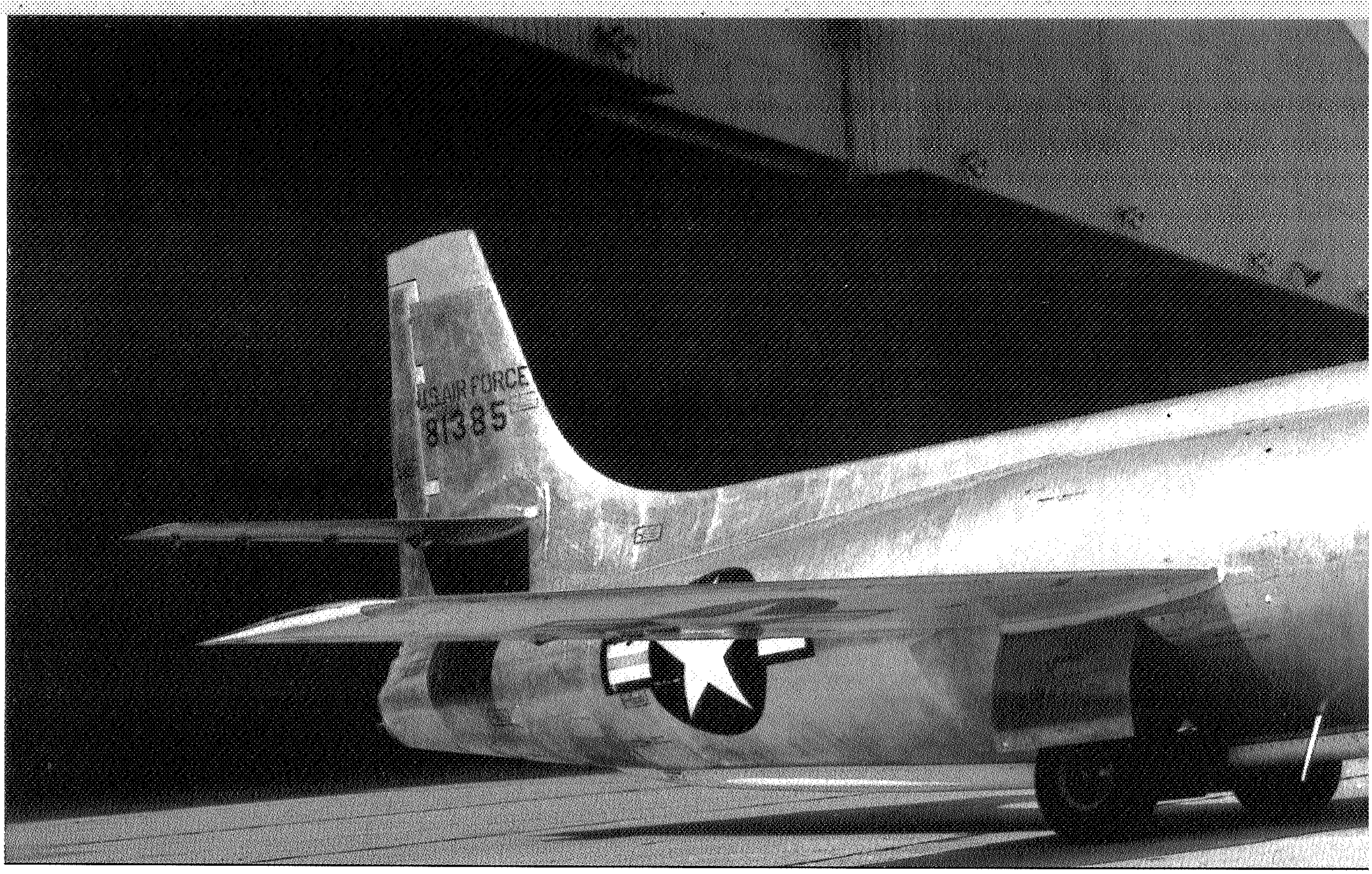
Testing the First Supersonic Aircraft

Memoirs of NACA Pilot Bob Champine



Excerpted from *Wings* Magazine, February 1991 Edition

This group portrait displays typical high-speed research aircraft that made headlines at Muroc Flight Center in the 1950s. The Bell X-1A (lower left) had much the same configuration as the earlier X-1. Joining the X-1A were (clockwise); the Douglas D-558-I Skystreak; Convair XF92-A, Bell X-5 with variable sweepback wings; Douglas D-558-II Skyrocket; Northrop X-4; and (center) the Douglas X-3.



In a scene that never was, test pilot Bob Champine stands next to the Bell X-1B. The problem is that Bob never flew the X-1B and the picture was taken at Langley, from where the X-1B was never launched. The craft, which was an X-1 that featured a revised cockpit among its many modifications as it explored thermal heating at high Mach speeds, was at Langley for some tests when the photo unit was asked to get some pictures. Since Bob had flown the earlier version, he was asked to be in these since, "No one will ever know..."

In the mid-1940s a new type of aircraft burned holes in the sky over the western United States. These were research planes, aircraft that were built with government funds for the specific task of learning more and more about high speed aeronautics and about what pilots and designers could expect as airplanes flew faster and faster.

In the past, aviation experiments had been conducted by hardy entrepreneurs who had an idea and then set out to prove the worth of that idea so they could sell it. Rarely was there any government money involved in funding such projects and aircraft used on those missions were normally regular military or civilian types that had been modified for a special purpose.

Even military aircraft were commonly developed as private ventures by manufacturers seeking major production contracts. If the government liked the idea, they bought a lot of them and the company made money; if it didn't, the company lost money and, sometimes, disappeared.

With the quantum leaps in technology that the maelstrom of World War II brought on, it soon became clear that the costs of developing new aircraft were becoming too high to allow private companies to routinely take the gamble. Besides, much was unknown! With aircraft going faster and faster, they were encountering the effects of compressibility. Could this be overcome? How? What about the mysterious "Sound Barrier?" Was it something that could be broken or would planes continue to crash against the barrier, sending their pilots to their deaths?

Melodramatic perhaps, but remember, no one had ever flown faster than sound and lived to tell the tale. What was out there? Whatever it was had just killed Geoffrey DeHavilland, Jr. as he attempted to break the barrier in the new DeHavilland DH-108 Swallow. His death caused the British to completely drop out of the speed race and the questions remained unanswered.

It was these questions and the many others raised by the postwar discovery of the tremendous amount of research that had been underway in Nazi Germany that made the U.S. take action. German scientists had been designing and testing planes without tails and planes with wings that were swept - both forward and backwards - plus planes that used rocket engines for propulsion and planes that had dozens of other strange and possibly wonderful advances. Were the Nazis crazy or might they have been on to something, or lots of somethings?

With those questions in mind, the U.S. government did something very different. It contracted for some airplanes. That in itself was not unusual. The unusual part was that these aircraft had no obvious purpose other than expanding our knowledge of aeronautics. The contracts specifically stated that the planes were not to be considered prototypes for fighters or bombers. Their range was often absurdly short and their carrying capacity was minuscule. Their sole purpose was to explore and document the unknown. Some were designed to just go fast. Some were designed to explore these funny new wings that were bent to the rear. One was designed to test the feasibility of planes without tails, and still another was a direct copy of a German plane that was to make use of wings that could have their sweep angle changed in flight.

Furthermore, the program wasn't just the result of a single good salesman getting a contract for his company. The contracts were spread around. Bell built the X-1, the X-2 and the X-5; Douglas built the X-3 and both phases of the D-558; Northrop built the X-4; and North American eventually developed its fantastic X-15.

As these new research aircraft came out they caught the public's imagination. Airpowe had achieved a new importance when th dawn of the nuclear age ended World War II Now these research programs promised to kee America on the leading edge of technology Most of the popular magazines of the da devoted both covers and space to the futuristi aircraft and the men who flew them. The made good copy.

The whole concept was exciting. Th movies and novels of the day promoted th danger with heroic test pilots going to thei death, their planes pummeled by the dreade sound barrier. *Into The Unknown* was popular film of the era and for the next te years the American public had something nev on which to focus its attention, and it was program that got results.

The Bell X-1 (known at first as the XS-1 proved that the sound barrier could be broken the Douglas D-558 project was to compar straight wings and swept wings at high speed and, eventually, the Phase II aircraft in tha project exceeded Mach 2. The Bell X-2 pushe

MACHBUSTER

A Test Pilot Recalls The Early Days Of Supersonic Flying, Where You Either Broke The Sound Barrier Or It Broke You!

By W.G. Williams

the speeds even higher; the X-3 explored the use of low aspect ratio wings, inertial coupling, the use of titanium, and led the way to the development of the Lockheed F-104 interceptor; and the X-5 proved the potential of variable geometry wings and led quickly to the short-lived Grumman F10F and later to the F-111, the B-1 and the F-14 Tomcat.

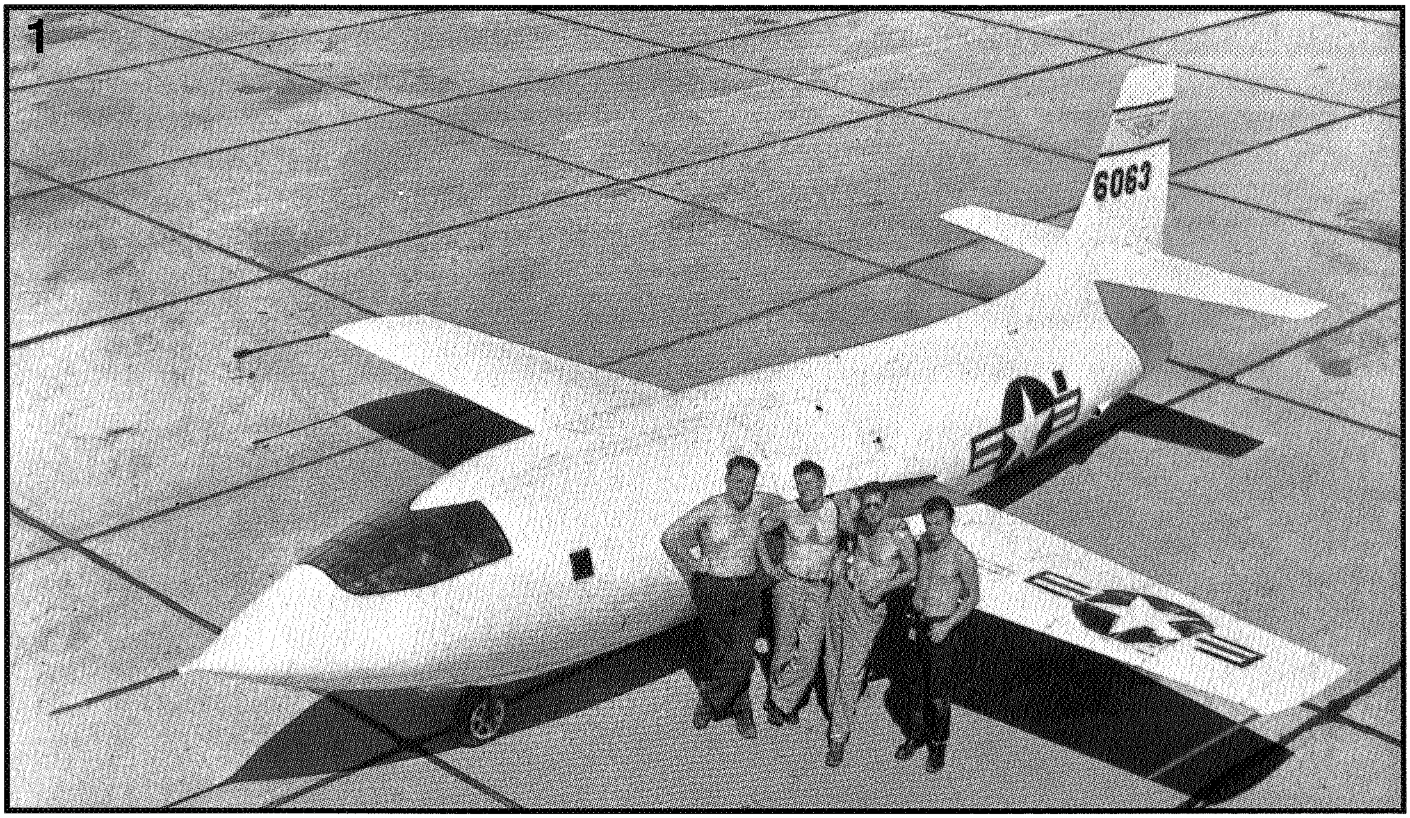
Another unique characteristic of the research aircraft program was that it had a variety of sponsors within the federal government. Although commonly thought of as an Air Force project, the research planes actually had several backers. The X-1 was contracted for jointly by the U.S. Army Air Corps and NACA (the National Advisory Committee on Aeronautics, the predecessor of today's NASA, the National Aeronautics and Space Administration) and while the first example was being flown by pilots from Bell and the Army, NACA sent the second bird back to the factory for major changes to the cockpit layout.

The Navy also was involved with the research program. It contracted with Douglas to build two types of aircraft that initially were to be identical, except that one would have straight wings while the second would have its wings swept at a 35 degree angle. As in many government contracts, later changes actually made these two aircraft very dissimilar. However, the Navy's program encountered a major problem that kept its aircraft from capturing the public's imagination, unlike the competition from their military brethren, and that was simply their designations. While the Air Corps/Air Force gave their planes the extremely sexy designation of "X-whatever," the Navy's two birds labored under the tongue-twisting and distinctly unsexy monikers of "D-558 Phase I" and "D-558 Phase II." The Douglas PR people tried to help by labeling the planes the *Skystreak* and the *Skyrocket*, but they never caught the public's attention like the "X" planes.

The first major hurdle for these aircraft was to exceed the speed of sound and return to a safe landing. Air Force Captain Charles E. (Chuck) Yeager was the first to accomplish this feat while flying Bell XS-1 #46-062 on October 14, 1947. At the time, the event was considered to be such a significant accomplishment that the fact that Mach 1 (the technical term for the speed of sound) had been exceeded was declared "Top Secret" and was not acknowledged until reports were leaked to the press several months later. Since then the story of that first flight has been told repeatedly in articles, books and movies. Now, over forty three years later, most people uninterested in aviation history have little or no knowledge of early research aircraft other than the X-1 and virtually no name recognition for any of their pilots other than Yeager.

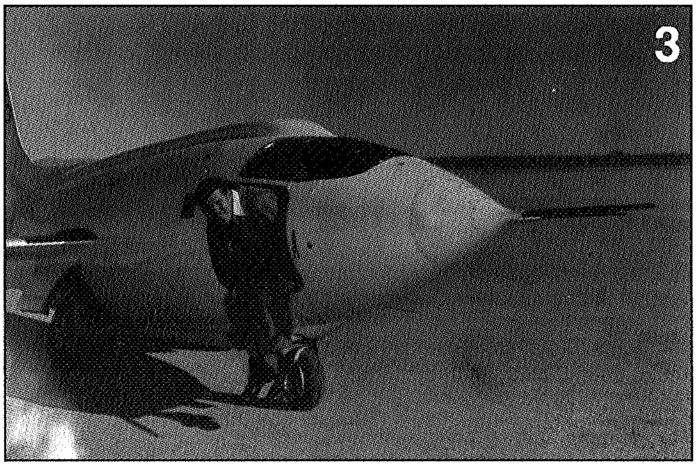
In addition, most of what has been written about these exotic flying machines primarily covers the cold, statistical facts of how often they flew, what speeds were reached on what dates, what types of engine they had, their length and span and other similar types of technical minutiae. Relatively little has been reported about what it was like to climb into one of these weird birds and try to fly them.

Robert A. Champine, who retired after a long career as the head of the pilot's section of the Research Flight Division at NASA's Langley Flight Test Center, was a young pilot fresh out of the Navy when he was hired by NACA as a pilot to fly P-51s. After a few months at the facility in Virginia, he was given the opportunity to go to Muroc Air Force Base in California to fly the X-1 and the D-558s.



1. **Flight test center at Muroc Dry Lake was hot and, since it was miles from the nearest town, uniform regulations were lax. Here four members of the ground crew gather for a group picture with the second model of the X-1.**

2. **The test pilot fraternity meets to discuss the problems that they encountered flying the new research plane. Here, in front of the X-1 and its mother ship are (left to right) NACA's Bob Champine, USAF Captain Chuck Yeager, and NASA's Herbert H. Hoover, who was the first civilian to exceed the speed of sound.**



3.&4. **Although the Bell X-1 was a small plane, it was stressed to take up to 18Gs because the designers had no idea of what forces would actually be encountered in transonic flight. Since the craft sat so low on the landing gear, getting in and out presented no problems while the plane was on the ground, as shown by Bob Champine, but getting into the craft while it was in the bomb bay of a B-29 in-flight was a bit more difficult. Because the door was placed directly in front of the sharp wing leading edge, exiting in an in-flight emergency would have been impossible. Fortunately, a bail out was never required, but close confines of cockpit are evident in Photo 4.**

5. Loading the Bell X-1 aboard the B-29 mother ship to be carried aloft required that the research ship be lowered into a pit and the B-29 then rolled over the smaller plane so that it could be hoisted into its bomb bay. Later, a system of hydraulic jacks was used to raise the mother ship.

6. Since the winds over Muroc Dry Lake picked up early in the day, most flights were made in early morning requiring the ground crews to work at night. Here the B-29 mother ship, with the Bell X-1 tucked neatly into its bomb bay, is bathed in harsh spotlights as it waits for dawn.

7. One of the first research aircraft Champine flew was the Bell L-39, one of two built for the Navy. Its wings were swept 35 degrees and its leading edge slats could be bolted on over different span lengths. Champine absorbed a great deal of aeronautical information flying this aircraft, which was especially valuable when he flew the Douglas D-558-II that incorporated slats on similar swept wing of 35 degrees, and he recalls that the L-39 flew extremely well.

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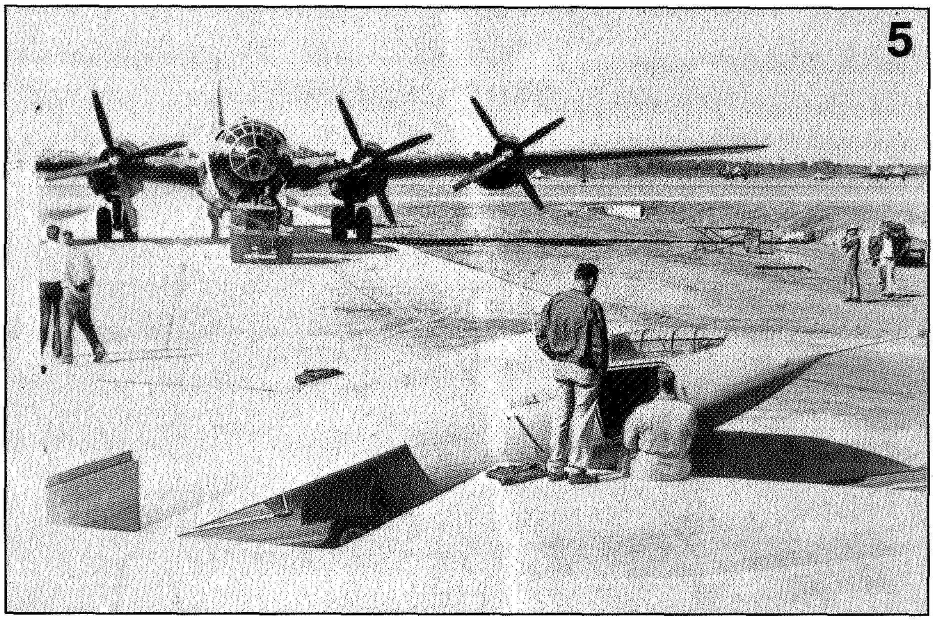

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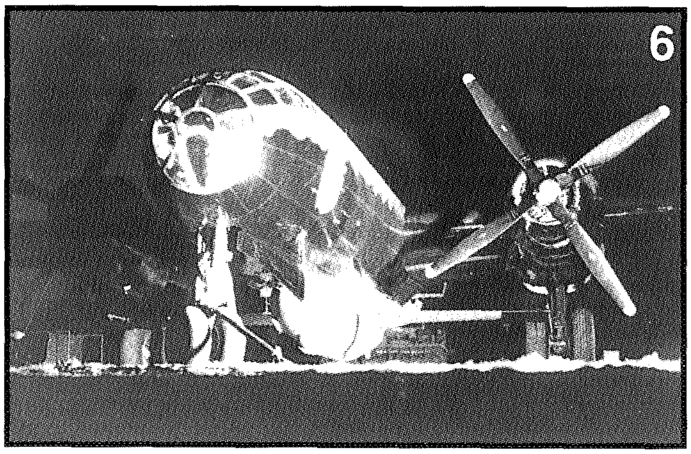

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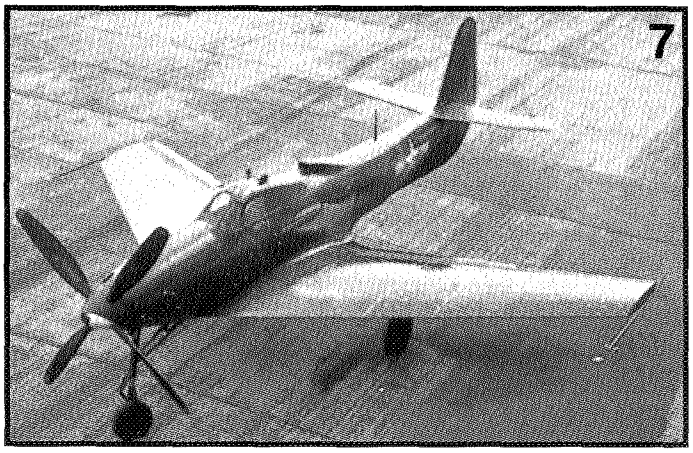


As one of the handful of pilots who have had experience in flying America's exotic early research aircraft, Bob was recently asked to recall and share some of his experiences and tell what it really was like to be a pilot in the world's fastest planes at the dawn of the jet age.

When Champine got out of the Navy and applied for a flying job at Langley, NACA officials tried to talk him into coming aboard as an engineer or a scientist, since he had a degree in aeronautical engineering from the University of Minnesota. Wanting to fly, he declined, holding out for a pilot's position. In the event that such a slot might not be available, he had covered himself by signing up to attend a VA-sponsored helicopter school at the Sikorsky plant in Connecticut.

"Melvin N. Gough and Herbert H. Hoover were the pilots' supervisors in those days and I didn't meet the requirements to become a test pilot when I applied at NACA. You had to have 1,000 hours of total flight time and I had 993. I told them that I planned to join the naval reserve as soon as I got out of the regular Navy and I would quickly be able to get those last few hours to comply with the rules. Since Mr. Gough had also been a naval reservist before World War II, I was told, 'Don't worry about it, you're hired.'"

Champine went to work for NACA in December 1947. "Langley had over 40 airplanes and I was assigned to flying the P-51s that had wing-flow models and balances attached to their wings. These were miniature models mounted above the thickest part of the wing so that the drag, lift and pitching moment forces on the models could be measured by optical balances. The technicians would install different airfoils, wings with different sweeps and different configurations on these models and we would fly the P-51 up to around 30,000 feet, put them into a 25 or 30 degree dive and go up to the limiting Mach number for the aircraft (about .72 or .73) to generate near supersonic or transonic flow over the wing. This was a way of getting high-speed flow and data from models. In the late 40s, wind tunnels were still not capable of doing this.

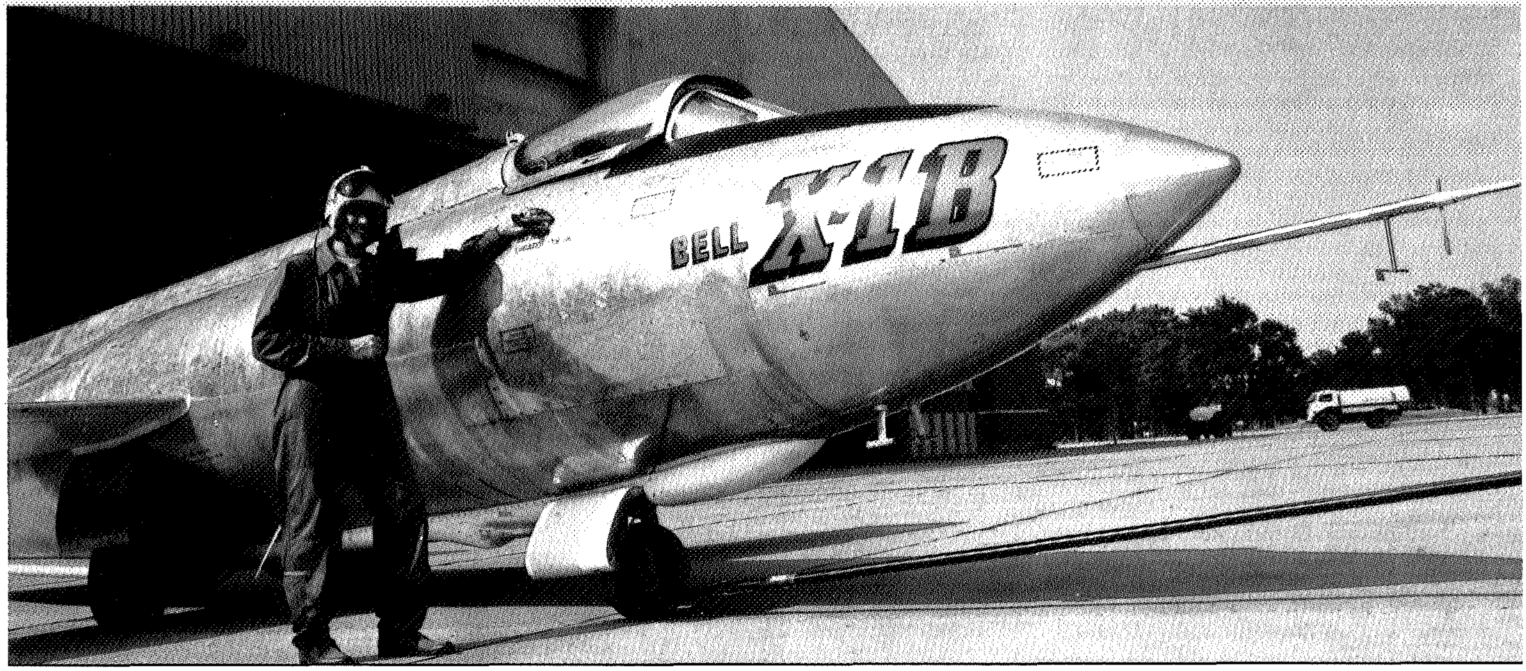
"We also had about a dozen P-51s outfitted with different models and different gloves, as they were called, over the wing bay. The pilots would take them up, turn on the instrumentation, dive them, come back and land. After the film from the optical balances had been developed and the engineers had measured the deflections on the film to generate the aerodynamics of the models, we'd do it all again. It was considered dog work and, as the 'new guy,' that was my assignment. New people always catch the stuff that nobody else wants to do...but I was tickled pink."

Since the X-1 program had actually started at the NACA laboratory at Langley, Herbert Hoover, Langley's head pilot, had been the pilot-in-charge. After the Bell pilots flight-demonstrated the XS-1, Hoover and Chuck Yeager started to expand the speed envelope to and through the sound barrier. Later, Hoover decided to pass the program on to another pilot and Howard C. Lilly from the NACA facility in Cleveland went out to Muroc. Champine met Lilly at a New Year's Eve party shortly after Bob joined NACA. Only three months later, Lilly was killed in a crash of the D-558-I when the engine failed, severing all of the craft's control cables.

"Mr. Hoover went back to flying the X-1 while still working here at Langley. When he needed to fly the X-1, he would take the C-47 that we had and fly it out to Muroc. The next day, after a rest, he'd get in the X-1 and perform the required flight; the aircraft would then be grounded and he'd come back to Langley until it was made ready for the next flight.

"When Lilly was killed, Hoover made a circuit of the NACA laboratories, looking for a test pilot to take over. When he couldn't get any of the old timers, he got down to the new boys. There was only one other new fighter pilot at Langley besides me, John Harper, and he didn't want the job. Everybody else's experience was in either B-25s, B-29s or PBYs, but all those guys were married and had children.

"There was a lot of spookiness about those research airplanes; one man had already been killed! There was a different way of flying the research craft and they were quite awesome for those days. Nevertheless, when they finally got around to me, I said, 'Yes!' But, since my experience level was pretty low,



I asked to be checked out in the airplanes that we had at Langley to build up my base of experience.

"Much to my surprise, they agreed.

"In addition to the P-51s, they had P-47s, a P-80, one of the first F8F Bearcats, and the L-39, which was a P-39 that had been modified with swept wings and fixed landing gear. Only the nose gear retracted because the wings were handmade. I was just dying to fly that one.

"There were multi-engined airplanes there, too, that fascinated me. We had two C-47s we used to maintain our IFR proficiency. We also had two B-29s and, although I had trained on patrol boats in the Navy, I was interested in learning to fly a larger four-engined landplane. My training for flying the research airplanes out at Edwards involved all these things. In the meantime, Mr. Hoover kept going back out to Edwards in the C-47 and continued flying the X-1."

As Champine prepared to move to Muroc, he spent a lot of time in the swept-wing Bell L-39. Its original program had largely wound down and the airplane had become a hangar queen. Because he was going to check out in it, NACA assigned mechanics to the thing, who brought it back to life.

"It was really a nice airplane. Its wing was swept 35 degrees and it had various configurations of slats that could be added to the leading edge. These slats were just bolted on in different span lengths; they could be put inboard, outboard or full span; they could be opened or closed. You could learn to fly a lot of different configurations that way and it was a marvelous opportunity to learn to fly swept-wing aircraft.

"It was also a marvelous opportunity to see what happened when you put flow control on a swept-wing; in other words, what happened when you had the slats open vs. having the slats closed. I developed a whole series of flight tests for my own benefit and later this served me very well in flying the D-558-II which had slats on the same 35 degree wing. I enjoyed flying the L-39 a lot; it flew great!

"As a side note, my friends were still in a Navy squadron over at Norfolk; so often, after having arranged for a rendezvous by telephone, I would fly some aircraft over and meet them at a certain place at a certain time. Once I found out that they were practicing carrier landings. Since I didn't have much to do, I joined them in the pattern with this weird swept-wing airplane and shot a few carrier landings. They thought that was really neat and it gave me landing experience which was valuable in my own little training program. But I didn't tell my boss or anybody what I was doing. It's only now, more than 40 years later, that I can tell the story.

"My introduction to swept-wing flight had a few surprises. At very, very high lift, particularly without the slats or with the slats mounted on the inboard side, the thing would pitch-up terribly. As you increased the angle of attack, you had to keep pushing the control stick further and further forward instead of pulling it back, and this is indicative of very bad stability. That particular plane flew quite well in that it always responded properly to the controls, but at high angles of attack, the neutral trim point of the control stick was always moving forward. Then it was unstable. Outside of that, it was a very nice airplane to fly."

In mid-1948 Bob Champine moved to the California desert test site at Muroc Air Force Base, which later became famous as Edwards Air Force Base. Chuck Yeager had exceeded the speed of sound months earlier and supersonic flight was becoming more of a common thing. Nevertheless, there was a lot to learn and the very first research planes, the X-1 and the D-558-I were still the workhorses. In addition, the site was being used by dozens of company test pilots as they tried to get the bugs worked out of their own firms' aircraft. Sharing the lake bed with the research fleet were such exotic prototypes as the Convair XF-92, the Lockheed XF-90, the Northrop XB-35 and XB-49 flying wings, and the uniquely parasitic McDonald XF-85.

While these military prototypes had two sets of test pilots, the company test pilots and the military test pilots, the research fleet had an added pilot from NACA and that's where Bob came in.

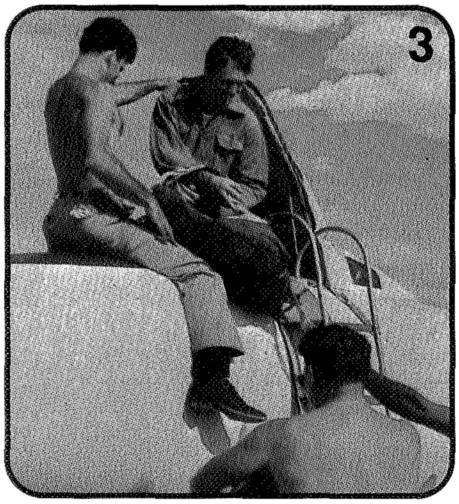
Since there were two X-1s, either could have been first through the sound barrier. Bob recalls that the flight program for NACA's X-1 (S/N 46-063) was several months behind the military because Herb Hoover had some serious objections to the craft's cockpit layout and he told Bell that it was unacceptable. He insisted that it go back to the factory to be modified and that change required about three months. As a result, the military plane had the lead in the race through the barrier.

Design of the Bell X-1 began in 1943 as a result of studies by NACA/Langley aerodynamicist John Stack and Bell engineer Robert J. Woods. Since data on the supersonic flight characteristics of aircraft was non-existent (even wind tunnels of the era were unable to develop the necessary wind speeds), the engineers relied heavily on the only information that was available. Since that material consisted of ballistics performance on the .50 caliber bullet, that provides the explanation of why the X-1 looks so much like a bullet with wings. After the first X-1 was delivered to Langley for inspection, the staff looked around for a suitable site for its first flight and settled on Florida. There the lack of open space quickly became a problem and all powered flights were later carried out at the Army testing center at Muroc Dry Lake in California. In 1948, as a result of the X-1's first flight through the sound barrier, the Collier Trophy was jointly awarded to John Stack, Lawrence Bell, and Chuck Yeager. Herbert Hoover received the 1948 Octave Chanute Award for being the first civilian to fly through the sound barrier. Several years later he was killed in an experimental flight in a North American B-45.

The military 6062 was never modified and the records show that the military pilots who flew 6062 had lots of difficulties monitoring certain gauges and operating some of the different valves. Champine recalls that 6062 continually had fires and lots of other problems, whereas the cockpit-modified 6063 flew for many years and few of its pilots ever had any trouble. It was a very worthwhile modification even though it did mean that 6063 with Herbert Hoover aboard did not exceed the speed of sound until several months after Chuck Yeager first did it in 6062.

Once on location, Bob's first opportunity to fly the X-1 came on November 23, 1948 and, after a couple of familiarization flights, he pushed the X-1 through the sound barrier for the first time.

1. The Douglas D-558 Skystreak was another of Champine's mounts. He remembers it as flying well up until Mach. 75, with good, stable handling and climb, but as soon as the shock waves hit above Mach .75, it became difficult to control. Designed by Leo Devlin, it had a flight duration of only 30 minutes on its kerosene type fuel, all of it stored in synthetic rubber-lined wing tanks. On May 3, 1948, test pilot Howard Lilly was killed shortly after takeoff, when the Skystreak's engine compressor disintegrated and one of the turbine blades cut through the plane's control cables.

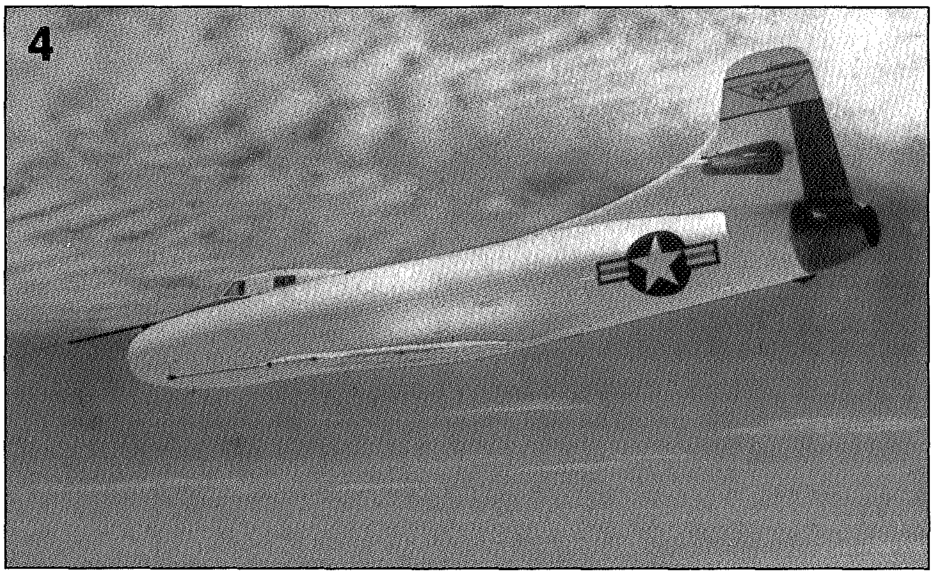


2.&3. In the early days of high speed flight, sophisticated pressure and anti-G suits had not yet been developed. As a result, the pilots basically strapped a parachute on over their work clothes, grabbed a helmet, and went flying. In these photos members of the ground crew are helping Bob Champine into the cockpit of the Douglas D-558-I Skystreak for a test flight.

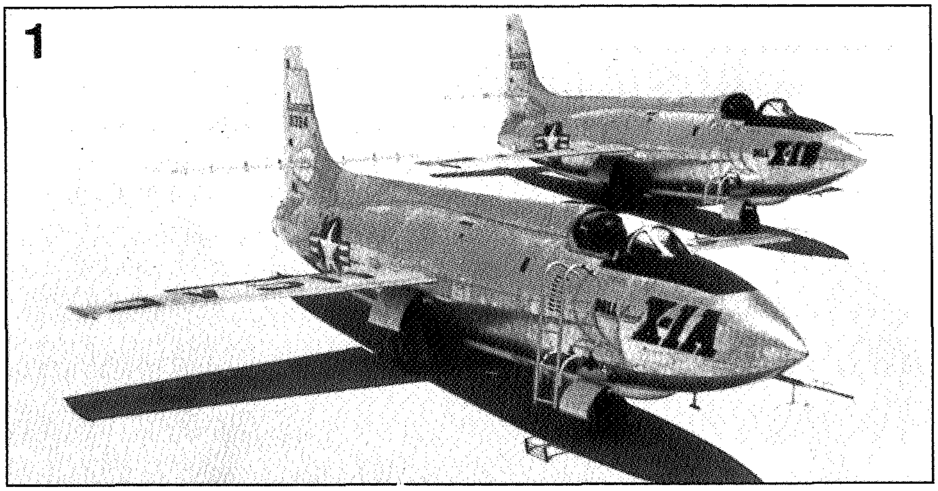
"My reaction was that it was a piece of cake. There was no problem; it was very easy to do. I was told that when I got to Mach 1, I should operate the controls through their full deflections. That meant I was to move the controls to full nose up, full nose down, full right roll, full left roll and to kick the rudders just to satisfy myself that the shock waves at Mach 1 left some control but that they were relatively weak at that speed. Since other guys had done it before me, I didn't worry too much and it was pretty much like they said it would be.

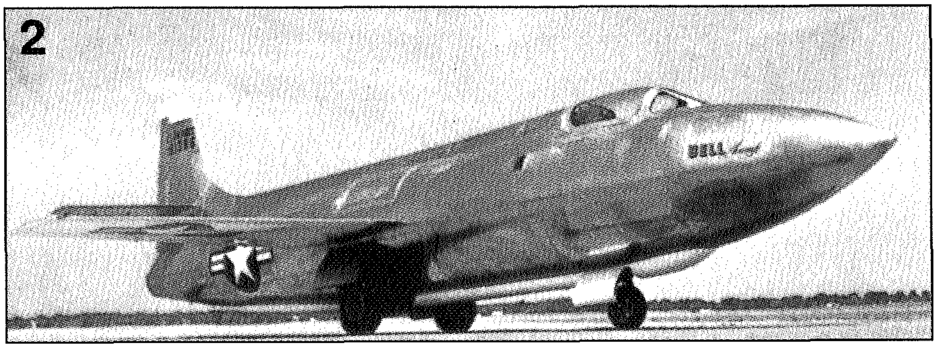
"It's true that there was a little tiny bit of buffeting and a little tiny bit of wing dropping or rocking laterally as I went through the speed of sound, but it was quite controllable. Although at Mach 1 the controls were not very responsive, as soon as you got through Mach 1, good control response returned because then the wing was all in supersonic flow; the shock wave was attached to the leading edge and the controls were in nice flow again, whereas when you were going through the speed of sound, the shock waves danced on the control surfaces and caused the loss of control. Being in a P-51 in a steep dive with the controls shaking would be of far more concern to me than being in the X-1."

Although the first transonic flight didn't have many surprises, Bob reports that: "The first subsonic flights in the X-1 were just one



4. The Douglas D-558-I Skystreak was designed to explore the high subsonic flight realms and did so quite economically for several years. Of the three examples built, two are presently on display. Note the family resemblance to the Douglas F3D Skyknight and the AD Skyraider. The tail surfaces are almost identical, while cockpit canopy served as model for that of F-102. See article in this issue on F-102 in Vietnam.





1. The three Bell X-1s were built to explore control forces at Mach 1; the next three second generation Bell research aircraft, the X-1A through X-1D, were built to investigate aerodynamic forces beyond Mach 2 and above 90,000 ft. They were larger and technologically improved, with thinner airfoils. It was in the Bell X-1A, on December 12, 1953, that Chuck Yeager experienced his wild ride as depicted in the film *The Right Stuff.* At Mach 2.4 and an altitude of 70,000 ft. the aircraft suddenly rolled out of control and began tumbling for 36,000 ft. It eventually went into an inverted spin, knocking Yeager into semi-consciousness. Fighting the controls, he managed to pull it out at 30,000 ft. After this, high speed flights were no longer undertaken in the X-1A, although it did reach an altitude of 90,440 ft. in August, 1954.

2. Bell X-1D had short career, just one flight. On July 24, 1951, its nose gear failed during landing.

3. Bell X-1E was notable for much shorter, thinner wing than its predecessors. On August 31, 1956, it reached a top speed of 1,480 mph.

thrill after another. Just dropping out of the bomb bay was a big thrill the first few times...a tremendous thrill...and it was scary. After you did it three or four times, though, and went back to the office and sat down and thought about it, you realized that it was a real cool way of getting airborne with a heavy and dangerous load of fuel. With an airdrop, you were able to *start* at around 25,000 feet and you didn't have to go through the takeoff and low-altitude climbout where, if you had a problem, you couldn't do anything about it. But, with an airdrop, if you had a problem after you launched, you could jettison the fuel and glide down to the lake bed. We became very ho-hum about it. It was very routine.

"We did not consider it very dangerous at all. In fact, my salary reflects that. I was out there flying those things on a salary of $2,600 a year and my lifestyle was very austere. I lived in a barracks and it was difficult for me to own an automobile. These barracks were very much like World War II soldiers' quarters; I think that Chuck Yeager may have complained about those living conditions in his book.

"The flights were considered just routine. It was a very ho-hum, eight hours a day kind of operation...for the pilots, anyway. However, you have to realize that in the California desert the wind picks up around noon and so we had to come in early in the morning to do our flying. As a result, the crew preparing the X-1 usually started loading L-O-X (liquid oxygen) and alcohol around midnight. It was a very slow thing because they had to cool down the aircraft like they do on the shuttle today. The loading of the fuels took a long time and the instrumentation guys came in really early to check out all the instrumentation to make sure everything worked and to install fresh batteries and film. Once the fueling started, only essential personnel were allowed next to the airplane, because if the L-O-X and the alcohol got together, there was an immediate explosion. Alcohol spillage of any kind was a dangerous situation.

"Once the aircraft was available for the pilot to go on board, it was very matter of fact, a 'Let's go fly today!' kind of operation. After I had been flying out there for about six months, I got a two step raise so I guess I was doing my job. I didn't ask for the raise; I was just delighted to be one of the flyers. I was like a kid with a new toy.

"The pilot actually entered the X-1 from the B-29 and we usually did that about 5,000 feet above the ground. That altitude had been chosen because, if you screwed up the works, from there you could get released from the B-29, jettison your fuel and still make a landing.

"Visibility through the canopy was very bad, but it was an increment better than looking over the nose of a P-51 on landing, and it was considered to be acceptable for those days. I thought it was even a little bit better than in an F4U Corsair. When you were at low speeds and high angles of attack coming around for a carrier landing in the Corsairs that I'd been flying, you simply couldn't see over the nose and had to look over the side. The X-1 was flown the same way.

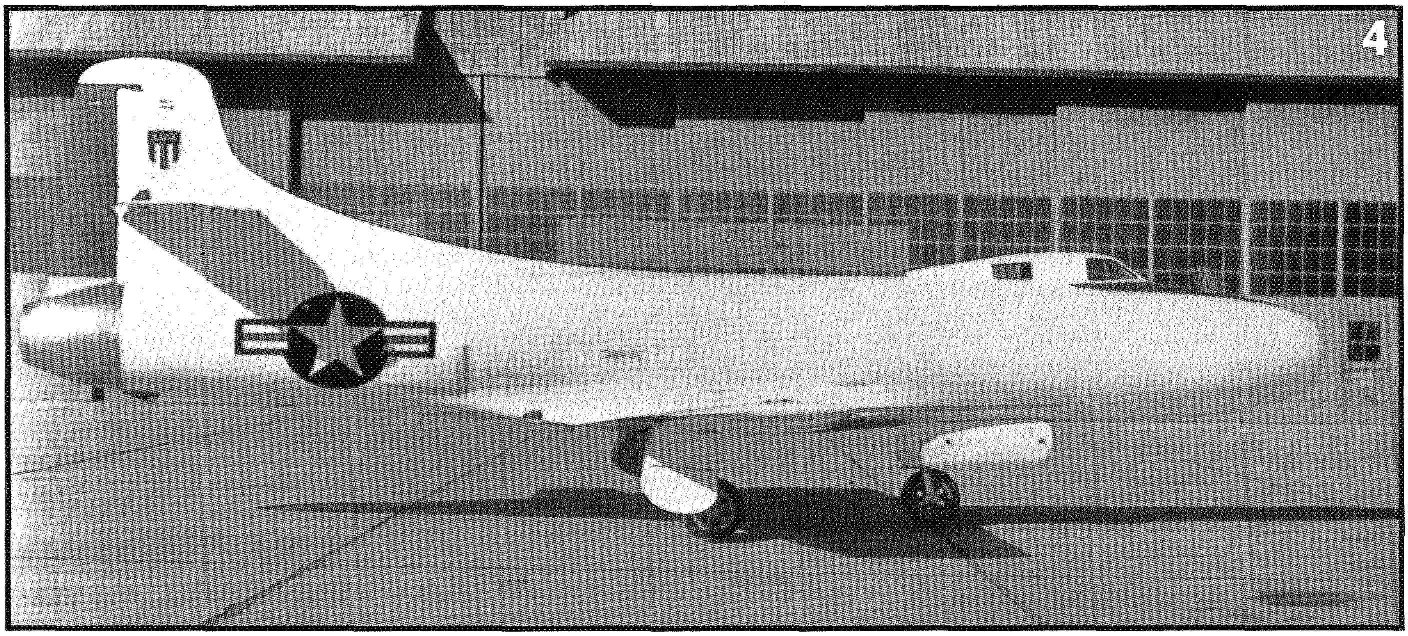
"However, when you were making an approach in the X-1, the dive angle was relatively steep because 220-250 miles per hour was the normal glide speed and the nose was down quite a bit. It had a good glide, though. It went a long ways, but when you flared and raised the nose for the actual touchdown, you couldn't see.

"The X-1 was very, very maneuverable. The only place it was deficient was from Mach .95 to 1.01, the transonic range where the controls were not very effective. At high subsonic speeds it was an excellent plane. I can remember Chuck Yeager doing slow rolls in it during his glides.

"When the X-1 was being carried to launch altitude by the B-29, there was always an intercom to communicate with the B-29 crew. When you got into the X-1 and put on your helmet and oxygen mask and got all settled, you would report that you had done so to the aircraft commander in the B-29. The radio communication was a part of the procedures that covered the safety aspects of everything.

"On one memorable flight, we were climbing to launch altitude, around 25,000 feet and, suddenly, I couldn't communicate any more. I had lost all contact with the bomber. I checked all my connections and they did the same thing at the other end, but we couldn't find the problem.

"Since we were very close to the drop altitude, I took my knee pad card and turned it over and wrote on it: "Secure the drop!" Now, I'd been in the Navy and to a Navy man, to 'secure' meant to stop doing something. I held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this up and showed it to the men, forgetting that it was an Air Force crew. The crew chief assumed that 'secure' meant that, even though I couldn't talk, I was all set up to drop.

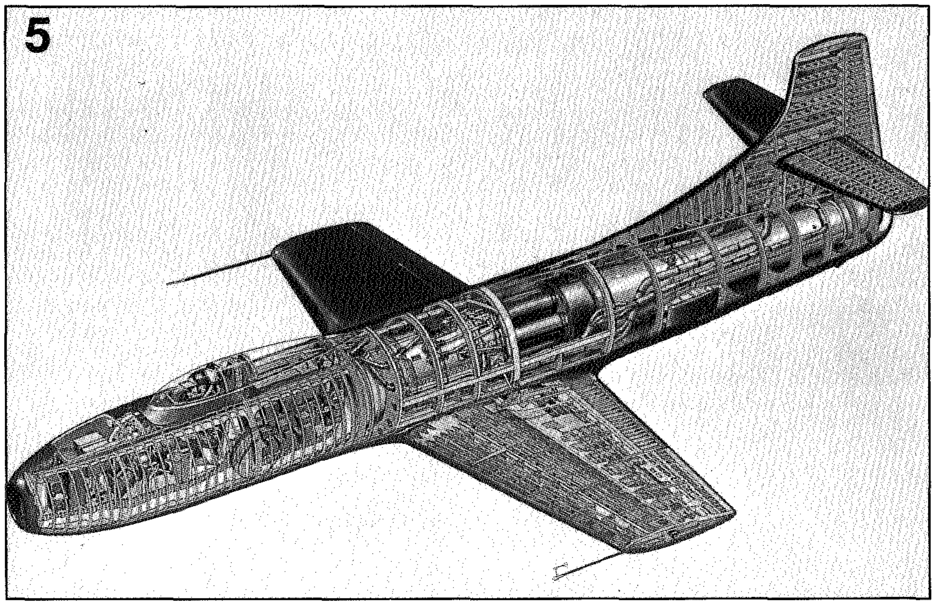
"As I sat in the X-1, I could see that the guys were getting ready to drop me. Well, I'm holding this card up and hollering at them and making noises as though I really don't want to go and all of a sudden I heard this little 'pop' as the bomb shackle broke loose and I was flying. Man, I wasn't ready to go anyplace and they're saying, 'So long, Bob! Have a god trip.'

"On that flight, it took some extra time but I did get everything set and I was able to run the rocket engines, do the flight card and make a successful flight out of it without talking to anybody. I still don't know why the radio didn't work.

"Later, as a result of that incident, I insisted that we install wiring for a light system. A red and green light appeared on the flight deck controlled from the cockpit of the X-1. If the aircraft commander had a red light, he needed to check before dropping the plane; if the light was green, he knew the test pilot was ready."

The impression many laymen have of these early research flights is that the pilots just fired the rockets to see how fast they could go as they tried to set new records with each flight. In practice, each flight was fully planned out with a specific speed goal and a preplanned set of experiments to conduct. "At every little speed increment, we had to operate the controls to measure the rolling velocities, pitching velocities and yawing angles at each of these Mach numbers.

"Keep in mind that when you ran the engine to maintain fairly high speeds, you didn't have much fuel. With one rocket chamber firing, the fuel usually would run out in ten minutes. If you fired three chambers, you could barely get through Mach 1 and you were out of fuel in about four minutes. With all the chambers firing, the flight was really short. After 13 flights in the X-1, I had only logged 1.2 hours! You had to accelerate, stabilize on your Mach number, do your maneuvers and, by then, you were out of fuel. You'd have to glide down, land, refuel, come back up again and do the same thing at a slightly higher speed. We made those flights repetitively to measure the flying qualities that could be found at the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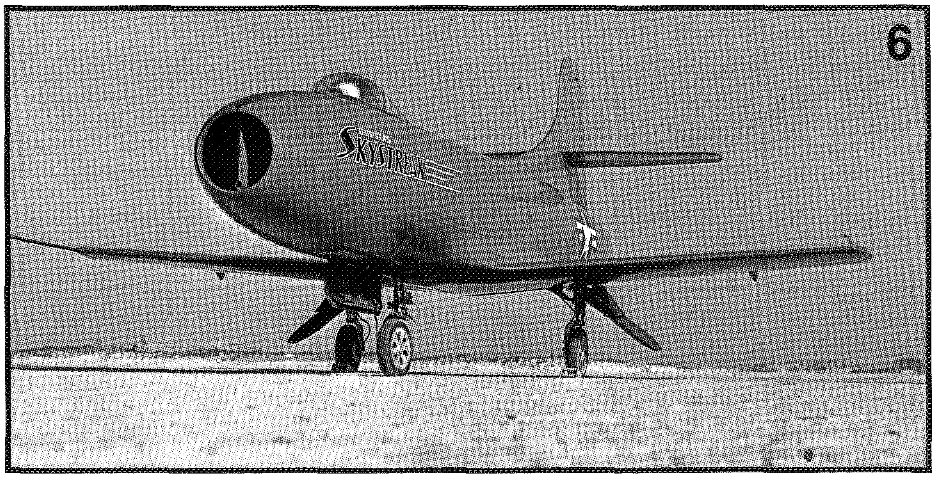
4.&5. While flying aircraft like the Bell X-1 and the Douglas D-588-I Skystreak, Bob Champine was paid a salary of approximately 50 dollars per week. Built of 75S alloy aluminum, the Skystreak pictured here and in cutaway was fitted with an air conditioner to cool cockpit temperatures to 100 degrees during high speed runs. The first Skystreak was completed in January, 1947, with the first flight taking place four months later on May 28th.

6. Skystreak as it appeared before installation of V-type windshield, as shown in Photo 4 and drawing No. 5.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different Mach numbers."

In addition to flying NACA's X-1, Bob Champine was also responsible for taking up where Howard Lilly left off when his Skystreak crashed. Bob's Skystreak, which has been restored and is on display at the Marine Corps Base at Cherry Point, North Carolina, was the last of the three to be built. The Skystreak (covered in the September 1985 issue of *Airpower*) was a straight-winged, jet powered research craft that was designed to explore high subsonic speeds. Although before Yeager's Machbusting flight in the X-1, the Skystreak held the world's speed record, it only exceeded Mach 1 on one occasion, when Douglas test pilot, Gene May, got it to Mach 1.01 in a dive on September 29, 1948. Its highest speed in level flight was actually Mach .99 while being flown by NACA's John H. Griffith almost two years later, on June 13, 1950, during its last flight.

Bob remembers the Skystreak as, "a very small plane with a very tight cockpit. It was fun to fly and it flew very well up to about Mach .75. It was easy to become very comfortable on takeoffs and climb outs and it had a good rate of climb, around 10,000 feet per minute, which was astronomical in those days, but the high Mach number characteristics were terrible. As soon as it got a shock wave on the wing, it had wing drop, control buffeting and shaking, and a feeling that it just wasn't going to go any faster. You could go into steeper and steeper dives and it just shook harder and harder and became increasingly difficult to control.

"When I landed on one of my earlier flights in the Skystreak, I had trouble seeing through the windshield; it seemed to have streaks on it. Now the windshield of that plane fit very, very tightly against my helmet (the only helmets we had in those days were military hard hats and they were really pretty big) and I realized that the problem was that the paint on the helmet was being rubbed off on the inside of the Plexiglas. To solve the problem, I stripped all the paint off the helmet and glued chamois skin onto it so that it wouldn't scratch the inside of the windshield.

"The Skystreak was a very small airplane that was fitted awfully tight to the pilot to cut down on the drag. In fact, you had to kinda scrunch down and pull your neck in to read the instruments; when you did that, you couldn't see outside and when you saw outside, you couldn't see inside. The smallness of the airplane was very dramatic...very claustrophobic. I was bigger than I should have been to be flying it.

"It had an axial flow jet engine in it with a good thrust-to-weight ratio. Even so, it started out slowly and accelerated slowly. We made all of our takeoffs on the lake bed for safety reasons, since it would allow us to roll as far as we needed. Outside of the fact that it had a small, confined cockpit, the Skystreak really was a neat plane.

"But like all the rest of these planes, it had minimum fuel. In fact, it had tip tanks available and, if we wanted to work at high altitude, we would use those tanks to climb until they were dry, jettison them and then climb some more. We didn't use the tip tanks on most flights, just because they were an extra expense and required extra time to install.

"A typical flight in any of these planes was to explore handling qualities at high speeds through control displacements. We had chains that had one end hooked onto the control stick and the other to the side of the cockpit and we would abruptly displace the control by pulling the stick against the chain. We could adjust the chain for one quarter, one half, three quarters and full deflection. While flying, we'd have to get down in the cockpit and rig up these chains and then deflect the control abruptly against the stop and then hold it until the airplane did its response and then you could bring it back to neutral and disconnect the chain and go on to the next point.

"We would fly at certain altitudes and certain speeds in order to plot out the control deflection vs. speed...particularly in the transonic regime. Knowing how quickly the airplane would respond to certain deflections could be equated to flying quality criteria and, as we got up toward Mach 1 or transonic speeds, we could see that the aircraft did not respond as well. Wing dropping, as we called it, was caused by a shock wave dancing on the wing or the control surfaces; it would wiggle the controls, making the aircraft begin to rock or oscillate. In spite of trying to correct with the controls, we couldn't keep its wings level.

"That reaction was important to know because it seriously affected the gun-aiming capability of any airplane. Good handling and flying qualities were vital to aircraft design, and learning about these problems was the purpose of these research aircraft.

"To document these responses, we had on-board recording equipment with just a bit of telemetry for the basic things like altitude and speed. The typical pilot's reactions on these kind of maneuvers was limited to saying, 'Well, gee, it really didn't roll very good', or, 'There was a terrible amount of buffeting after I deflected the control', or, 'When I did the pull-up against the chain, there was pitch-up and it was difficult to control.' Those comments from the pilot were always sought after, even if they weren't very scientific."

The second phase of the Douglas D-558 program was popularly known as the Skyrocket. Originally conceived as a Skystreak with swept wings, the Phase II changed dramatically, until it appeared at its rollout as a needle-nosed craft that looked more futuristic than many of those drawn in comic strips. Like the Phase Is, three Phase II aircraft were built and were flown by Douglas, Navy, Marine and NACA test pilots. Originally powered by jet engines and employing a regular takeoff like the Phase I, engineers soon saw that more power would be required.

"Since the NACA Skyrocket, S/N 144, was delivered to us as a brand new airplane that had never been flown, I had the privilege of making the very first flight. It only had a Westinghouse J-34, a puny little engine that didn't have much thrust.

"Gene May, the Douglas pilot, had been flying the earlier example of that airplane and by this time, his had a rocket engine installed in addition to the jet. Each one of its rocket's four chambers put out 2,000 pounds of thrust, whereas on the X-1 each chamber only put out 1,500 pounds.

"I never was allowed to fly that airplane, since its flights were for company development tests and for the Navy. If the Navy wanted specific runs done, they were done in that airplane or the third, which came along later.

"With only that small jet engine in it, 144 was not supersonic. Later, after I left, they installed a rocket, dropped it from a Navy B-29 (PB-1W), and eventually it reached Mach 2. Today 144 is hanging in the National Air and Space Museum in Washington, D.C.

"When I flew the original 144, we had to use two JATO bottles to get it going fast enough to take off. When the flaps and the gear were down, it would not get airborne with just the power from that jet. I would run on the lake for about a mile to get it going as fast as I could and then fire the JATO. With the JATO, I could just get enough speed to take off and retract the landing gear. Getting the gear up would give me enough extra speed to let me retract the flaps, and by then the JATO would run out. I'd dump the JATO bottles at the end of the lake and then it would finally fly. It was not very enjoyable. (It had been demonstrated on the company airplane that four JATO bottles could be used. Using two was a compromise between what we needed to get us going and the need to keep costs down. If we had used four, it would have cost twice as much for JATO bottles.)

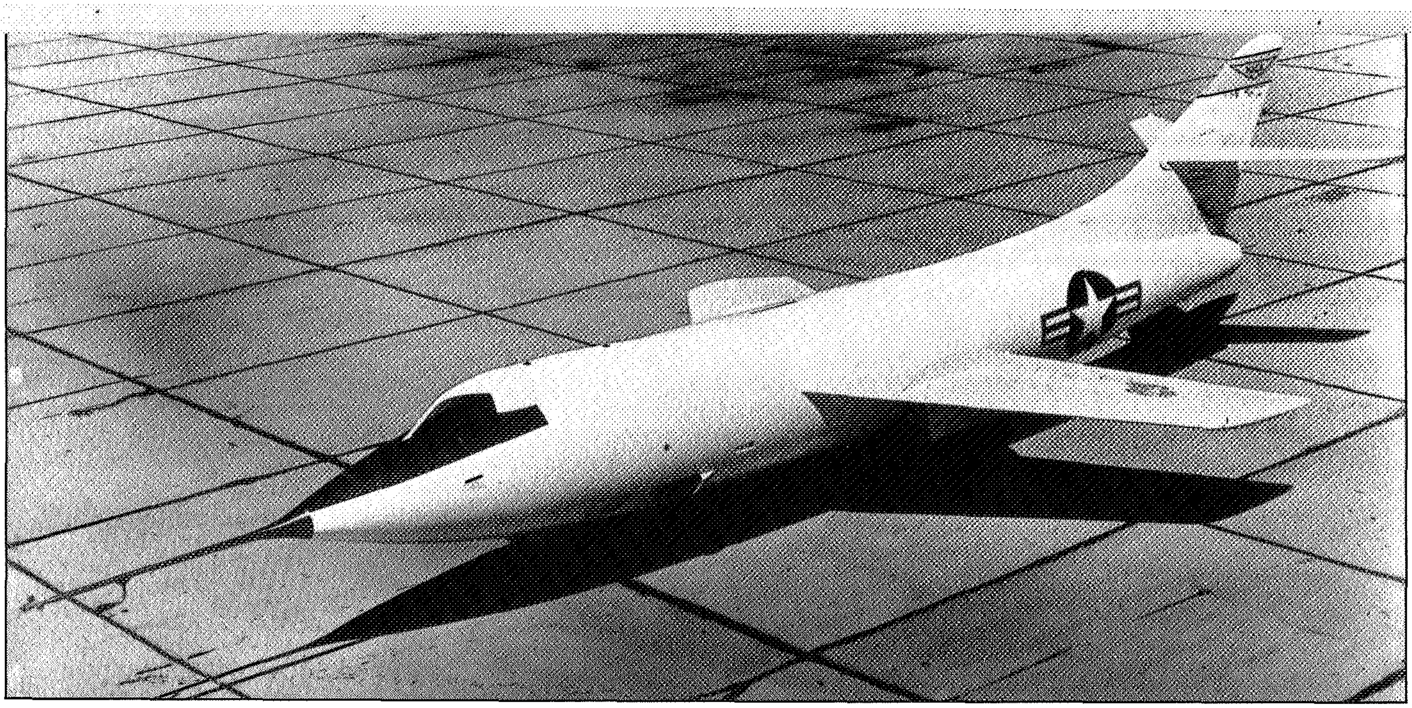
"Subsonically, it didn't fly too badly...except that in the landing configuration it had a terrible Dutch roll. In fact, on my first approach and landing, I wasn't sure that I was going to make a landing and survive. It would continually roll plus or minus 15 to 20 degrees for a period of about two seconds. Although I was constantly moving the aileron right behind it, I was probably amplifying the problem. I learned that if I punched it a couple of times with the ailerons to stop the roll, it would settle down by itself. When I leveled out in straight flight and raised the nose for the touchdown, then the dampening became pretty positive and it stopped...but it was kinda scary for a while. I briefed every guy who flew it after me and said, 'You're not going to crash. You'll control it...in the end...right before landing. But you'll have serious doubts until that point.' We got used to it, but it was never very comfortable.

"There was one other bad thing about that airplane. At high altitudes and at high angles of attack, it had a very violent pitch-up. If you pulled up and got it to 4 or 5 Gs, it would suddenly stall in such a manner that the lift distribution on the wing would cause it to pitch-up violently. It would go to extremely high angles of attack, between 45 and 60 degrees, and then it would start to roll violently, so the aircraft became completely and totally out of control - just spinning around in the sky.

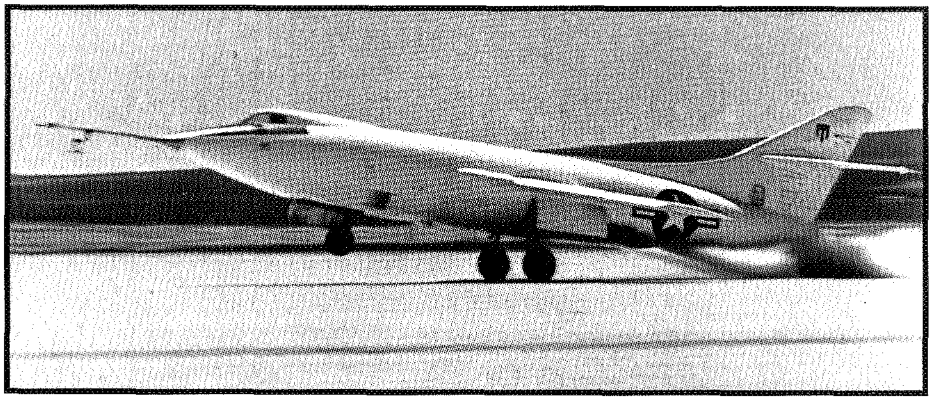
"The people who were responsible for these aircraft were scared to death and they criticized me very severely the first time this occurred. They said, 'You never should have let it happen. You're supposed to be a good enough pilot that these things don't happen.' But when they got a look at the instrumentation, everybody was terrified, because all the instruments were going bananas. Other pilots explored that area again and experienced the same problem; the airplane was simply out of control. Once you fell into it, you had no way of controlling it. You just had to ride it out until you eventually were falling nose down in a spin.

"Once you were able to unstall the wing with nose-down elevator, you just used opposite rudder and it would recover in a vertical dive. It was just a matter of sitting there until it stabilized in a spin. You then used spin recovery techniques and it would recover and come out of it. It wasn't all that dangerous except for the fact that the pitch-up was a brand new problem caused by shock waves on a swept wing. Later airplanes, particularly the F-100, experienced this same problem.

"Now you have to remember that not



The much improved, swept wing Douglas D-558-II Skyrocket was originally designed to take off under jet power and then use on-board rockets for high speed runs. When the first planes were delivered, the rockets had not yet been installed and the first test flights were made on jet power alone. Unfortunately, the engine originally installed could not even provide takeoff power and so JATO bottles had to be used. Although capable of using four JATO bottles, in the cash-strapped period following World War II, the NACA crews only made use of two bottles, per flight to save money. Champine made the first flight in the Skyrocket, before it was fitted with rocket engine.



much was known about shock waves at that time. While scientists in the wind tunnels understood what shock waves were, they didn't know how to handle them. In diving the P-51s with models on the wings, we could look out on the wing and see what was going on. If by chance we were in a certain orientation to the sun, we could actually see the shock wave. The light was dispersed in some manner so a shadow was cast through the shock wave and, as we would maneuver to adjust the dive angle and hold our speed, we could watch the shock wave moving around on the wing. This was a whole new thing and people used to say, 'Aw, you're crazy! You're not sure of what you're seeing.'

"But we were seeing the real thing! On today's jet airliners, if the sun is oriented just right, a passenger can look out on the wing and see the shock wave. Although the sun has to be just right to cause this shadow, the shock wave is there all the time.

"Research airplanes were great in terms of opening up a lot of new ideas on controllability at transonic speeds and that was the name of the game. When they designed the Century Series fighters, these research planes had given designers a lot of information to go on in terms of controllability, stability, shifts in stability and shifts in tailplane orientation. All the Century Series had movable stabilizers because the research aircraft found that when you move the horizontal stabilizer at high Mach numbers, the controllability was excellent whereas moving the elevator didn't do anything. That led to the development of the all-flying tail surfaces for elevator control.

"A lot of other things were learned, too. Airfoil shapes became thinner and thinner. The two X-1s, 6062 and 6063, had airfoils of different thicknesses and the drag that was noted on the thicker airfoil made us realize that we needed thinner airfoils in the supersonic regime. Since so much was learned with those first ones, we went on to develop other research airplanes, like the X-3, the X-4, the X-5 and the X-15. The X airplanes did contribute a great deal to improving the knowledge of transonic flight.

"These later aircraft offered dramatic changes in design philosophies. I was on the mock-up boards and participated in making decisions about their design and operating procedures. Although many of these were not good flying airplanes, they resulted in aeronautical knowledge that allowed the industry to build some good airplanes.

"The early research airplanes continued to be flown for quite a long time. Other pilots, like John Griffith, Scott Crossfield, Stan Burchard and a whole raft of others, came along after me and flew the same basic airplanes configured a little differently, with thinner wings or more tail surface or something else that was intended to improve the aerodynamics."

Bob Champine was at Muroc less than two years before he requested a transfer back to flying duties at Langley. His reason for the request: boredom!

"I wanted more flights. Flying the research airplanes was a big deal but, when you consider that in over a year I only flew 13 flights in the X-1 and seven or eight flights in the D-558-I and maybe six or seven flights in the D-558-II, that's not much. Although I was the only NACA pilot at Muroc, they just couldn't turn the flights around any faster with the personnel, equipment and funding available. Remember, this was just after World War II and the thin allocations from Congress just didn't cover much.

"What I did the whole time I was at Muroc wouldn't even represent one month of flying back at Langley. There we had 25 or 40 active airplanes and a lot of projects to fly. If it had not been for flying the C-47 and the C-45 on our regular flights to Los Angeles and the flying I did with the naval reserve, I would not have even been able to keep current. I just didn't feel as though I was contributing anything."

After his return to Langley, Bob Champine went from the world's fastest aircraft to the slowest, in that he became a specialist in helicopters and V/STOL aircraft and active in turbulence and vortices studies. He participated in the space program and was the first pilot to test the Lunar Landing Module that eventually would take Neil Armstrong and Buzz Aldrin to their historic rendezvous. Bob Champine did not actually fly to the moon, but without his expertise and the dangerous flights he and many others made on the threshold of space, there would not have been a moon flight and aviation might still be stalled at the sound barrier, trying to discover a way through it and beyond, to the stars.

1917 - 1992
75 Years
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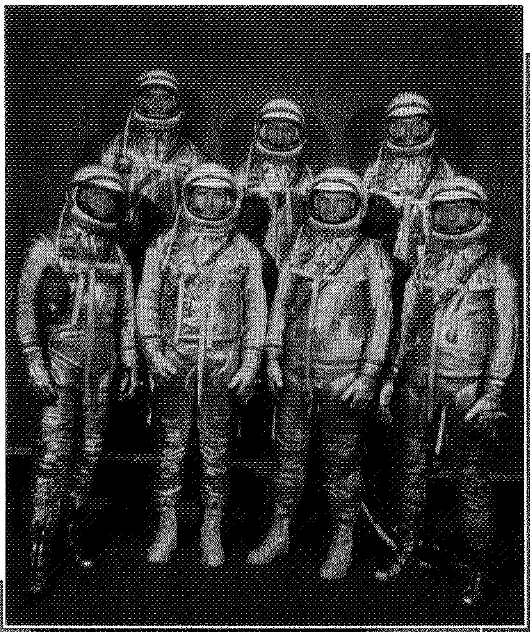
NF169 - November 1992

NASA Langley Research Center's Contributions to Spaceflight

(right) NASA's seven original astronauts trained at Langley for Project Mercury. Top row from left, Alan Shepard, Virgil "Gus" Grissom, Gordon Cooper; bottom row, Walter Schirra, Donald Slayton, John Glenn and Scott Carpenter. Shepard was the only one from the group to walk on the moon.

(far right) Launch of the highly successful Scout launch vehicle, used for unmanned small satellite missions, high-altitude probes and reentry experiments. Scout was managed by Langley from 1957-1991.

(bottom) The Langley managed Viking 2 lander on Mars' Utopian Plain, September 24, 1976 - America's bicentennial.



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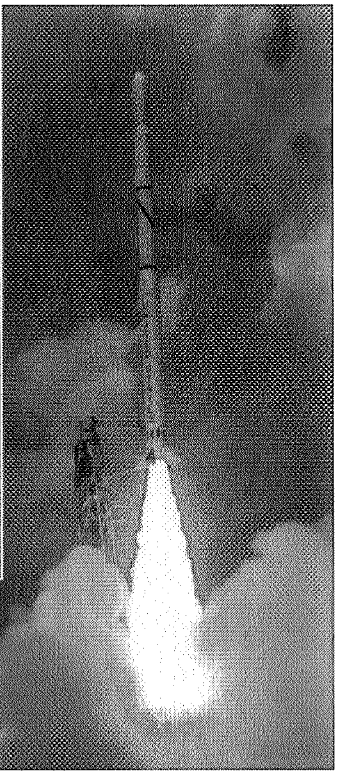

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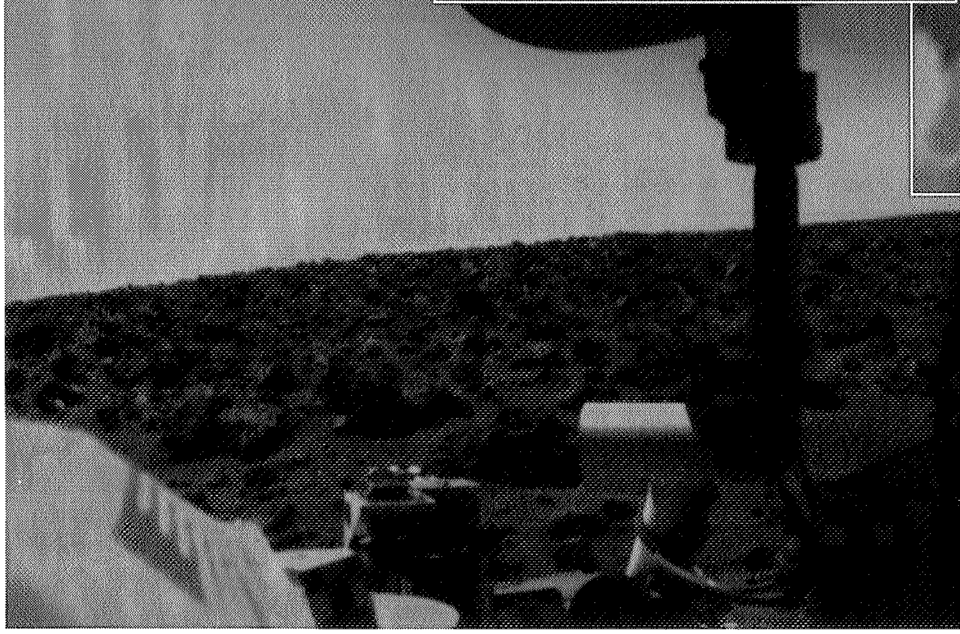

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For more than 75 years, scientists and engineers at NASA Langley Research Center in Hampton, Virginia, have been turning the dream of spaceflight into reality.

This Promethean task has required Herculean labors. At Langley, researchers have adapted wind tunnels and other sophisticated equipment, much of it designed originally for aeronautical research, into tools for the study and promotion of spaceflight. They have built complex simulators and other subtly responsive interactive devices to explore the feasibility of traveling and occupying the foreign environment of space.

Langley researchers have nurtured and fought for ideas, concepts, and technologies that ultimately proved essential to the success of such major manned space projects as Mercury, Gemini, Apollo, Skylab, and the Space Shuttle. They have spearheaded such major unmanned exploration projects as Echo, Lunar Orbiter, and Viking.

They have developed a reliable, low-cost, solid-propellant booster rocket, the Scout, that has put hundreds of scientific research payloads into orbit.

And on several noteworthy occasions the concerted efforts of Langley researchers have worked to overcome a specific problem plaguing the development of a particular piece of spaceflight hardware. A noteworthy example of this tradition of "fire fighting" in support of the space program is the work carried out at the Center in the 1970s and 1980s to perfect the Shuttle's thermal protection system, the tiles that protect the spacecraft from the intense heat of reentry into the atmosphere.

Without the help of the fundamental information about spaceflight that only a basic research organization like NASA Langley can provide, no space program—past, present, or future—could hope to succeed.

HQ-62-MA6-48
Astronaut John Glenn entering Mercury spacecraft "Friendship 7" during prelaunch activities. Glenn became the first American to orbit the Earth on February 20, 1962.

A Heritage in Aeronautical Research

Some might find it curious that a research center whose heritage is so deeply rooted in the study of airplanes could make as many basic contributions to the achievements of spaceflight as has NASA Langley. After all, no rocket has ever been launched from the place; not a single Space Shuttle has landed there. Everyone knows that Cape Canaveral, Florida, has the launching pads; Houston, Texas, Mission Control; Huntsville, Alabama, the rocket firing test facilities; and Edwards Air Force Base, California, the dry lakes for landings of high-speed vehicles. But what does Langley, in tidewater Virginia, have to do with spaceflight?

The uninitiated visitor to Langley, pausing to ask that question, may be surprised to hear the answer: quite a lot. Langley is in fact one of the only three or four places in the country that can make a legitimate claim to being the birthplace of the American space program.

That is a remarkable claim for an organization whose roots go back to the fragile wooden biplanes of World War I and whose specified mission for the next 40 years had nothing directly to do with realizing the dream of spaceflight.

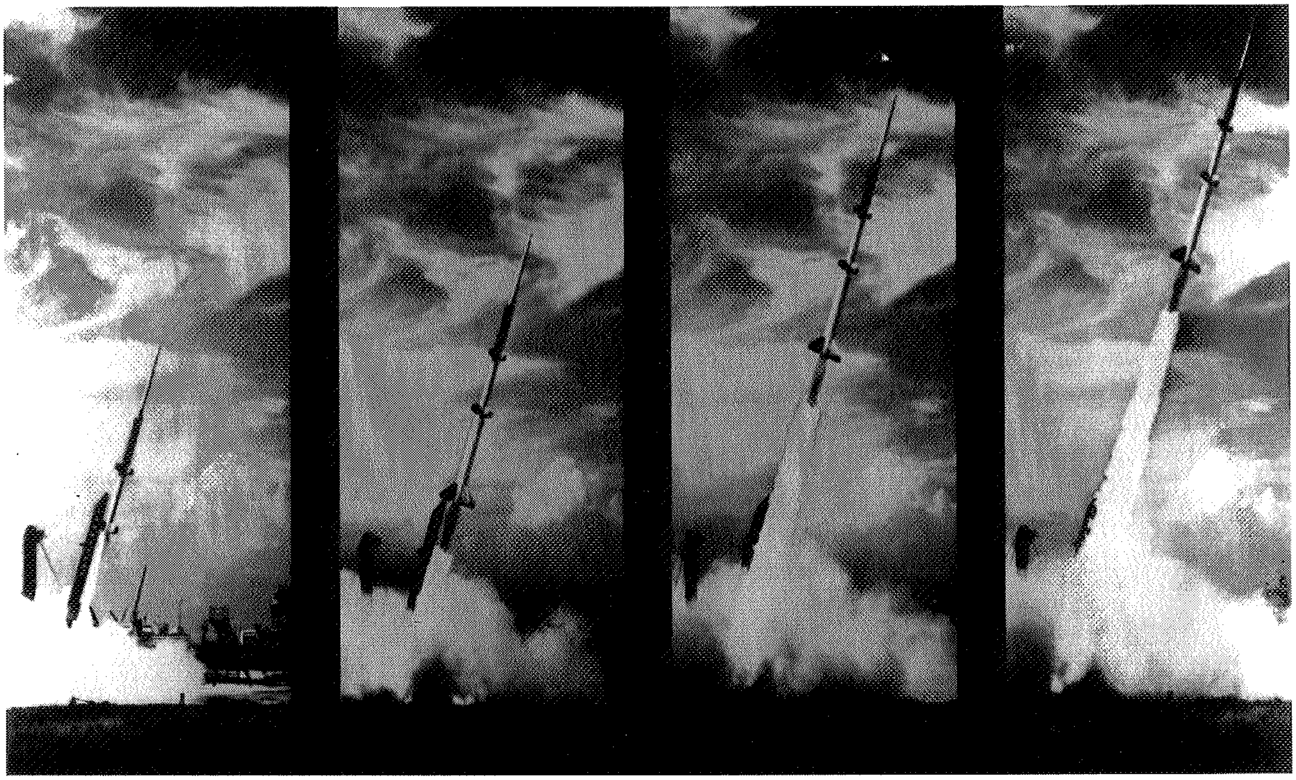
Long before the idea of spaceflight captured the American public's imagination and led, in the wake of the Russian Sputnik, to the creation of the National Aeronautics and Space Administration (NASA) in 1958, Langley researchers were seriously contemplating ways by which to turn the idea of atmospheric flight into reality.

As members of the Langley Aeronautical Laboratory, the oldest and largest facility of the National Advisory Committee for Aeronautics (NACA), they played a vital role from 1917 to 1958 incubating the ideas and hatching the technology that allowed American aviation to take off and fly.

In wind tunnels and in actual flight research, they tested nearly every American production aircraft built, and found ways, little and big, to improve upon most of them. During World War II alone, NACA Langley tested 137 different airplane types, representing more than half of all the types contracted for by the Army and Navy during the war and including virtually all types that actually saw combat service.

During the war Langley researchers also played a part in the development of the jet engine, and they observed with much greater interest and deeper insight than most people the practical appearance of such revolutionary new technologies as atomic energy and rocket propulsion.

From their station at the cutting edge of aviation technology, it did not take Langley scientists and engineers long to realize that their growing knowledge of high-speed aerodynamic problems translated nicely into solutions to problems posed by the flights of rockets and guided missiles. In the years immediately after the war, they moved quickly to investigate such bold new possibilities as flying a new breed of vehicle to the edge of the atmosphere and beyond.


L-90-3743

Takeoff of a five-stage missile research rocket from Wallops Island, Virginia in 1957. The first two stages propelled the model to about 100,000 feet and the last three stages were fired on a descending path to simulate reentry conditions of ballistic missiles.

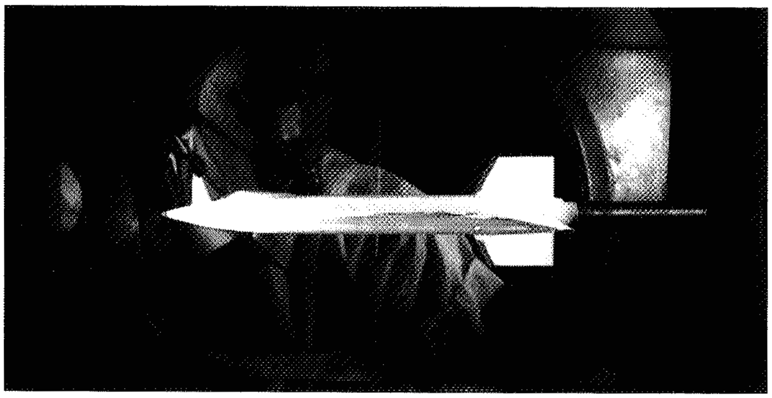
Transition to Space

Even before World War II ended, NACA Langley established a rocket testing range at nearby Wallops Island, Virginia. From its remote beaches on the Atlantic, a small team of researchers launched small rocket-powered models weighing about 40 pounds. These pilotless, finely-instrumented models shot up into the air to a velocity of just one under one half times the speed of sound (Mach 1.4), continued upward, and then dived into the ocean. Using radio telemetry and eventually Dopplar radar, NACA technicians on the ground tracked the models and gathered basic data about their overall aerodynamic performance.

The rocket-model testing technique was designed originally to produce meaningful information about transonic and supersonic flight—data that for technical reasons could not yet be produced in any wind tunnel. The NACA's idea was then to apply that precious data to the design of the high-speed jet and rocket powered aircraft that were then on the drawing boards. These aircraft included the experimental Douglas D-558 and Bell X-1, the first aircraft to assault the mythical "sound barrier."

The rocket-model testing done at that marshy barrier island provided information invaluable to the successful design of the first aircraft to fly supersonically. Ultimately, however, it came to signify much more.

The experience of systematically instrumenting, launching, and tracking rockets from an installation of their own making prepared the Langley personnel for many of the early tasks in the American space program. The people and facilities that grew up around what in those days was known as Langley's Pilotless Aircraft Research



L-59-6297

A Langley technician inspects a wind tunnel model of the X-15 hypersonic research aircraft in the 1950s. It became the first vehicle to fly into the fringes of space (50 miles high).

Division, or PARD, were to make several basic contributions to the Mercury, Gemini, and Apollo manned spaceflight programs.

As a matter of fact, the Space Task Group that conceived and managed Project Mercury, America's first man-in-space program, came in large part from Langley staff whose formative experiences had been in rocket-model testing and upper atmosphere studies at Wallops.

At the same time that PARD was shooting rockets into the ionosphere, a small cadre of innovative thinkers back at the mother laboratory in Hampton began to design experimental vehicles that could, at least on paper, fly fast enough (or be boosted atop a rocket high enough) to jump out into space.

Four major types of manned vehicles capable of spaceflight were studied at Langley and the other NACA laboratories: the rocket-powered airplane, the hypersonic glider, the lifting body, and the ballistic capsule.

A rocket-powered "space plane," the North American X-15, was actually built, much of it according to hypersonic concepts and wind tunnel data provided by engineers at NACA Langley.

In June 1959, nine months after the dissolution of NACA and the establishment of NASA, the original X-15 made its first flight. One of the first NASA pilots to fly the plane was Neil A. Armstrong, who, within the decade, would be the first man to walk on the moon.

Until the first orbital flight of the Space Shuttle Columbia in 1981, the X-15 held the speed and altitude records for winged aircraft, with flights as fast as 6.7 times the speed of sound and as high as 67 miles. This was far above what authorities recognized as the fringe of space.

The X-15 program ended in 1968. In many aspects, its design and audacious performance led the way to the Space Shuttle.

Furthermore, if not for the fact that the United States lacked a powerful enough booster in the 1950s, the country's first manned spacecraft might have been one of the hypersonic gliders conceived at Langley. Or it might have been a landable winged vehicle akin to a small Space Shuttle. As it turned out, however, it was to be a ballistic capsule that parachuted into the sea.

During the first 40 years of Langley's operation, the idea of working seriously to promote the immediate achievement of spaceflight was considered foolish. As the agency of the federal government responsible for the progress of the country's aviation technology, the NACA had enough to do without getting involved in what was then considered to be "Buck Rogers stuff."

In other words, space was a dirty word in the American political arena. One Langley veteran recalls that the NACA stood as much chance of "injecting itself into space activities in any real way as an icicle had in a rocket combustion chamber."

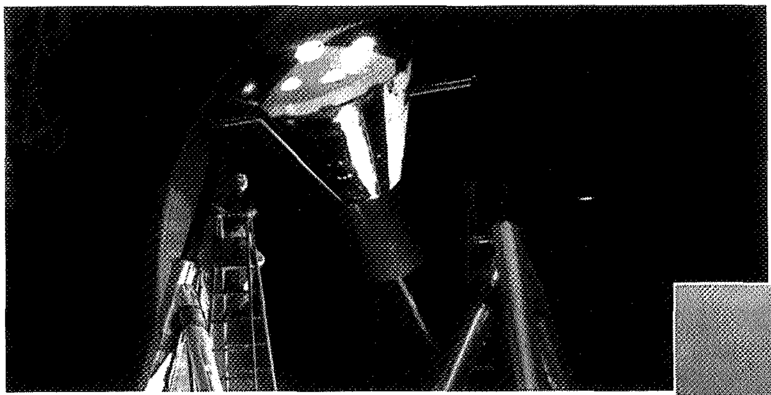
Sputnik and the Birth of the American Space Program

One event changed all this: the Sputnik crisis. Nothing triggered the explosive growth of interest in spaceflight in the United States more than the Soviet Union's unexpected launching in October 1957 of the world's first man-made satellite.

Fortunately for the country, the NACA's mission had been broad enough to allow its researchers the freedom to probe the fundamental questions challenging the natural extension of atmospheric flight. For them, the Space Age had already started. From tests conducted in hypersonic wind tunnels, expansion tubes, electric arc-jets, and other types of advanced high-speed and high-temperature facilities, Langley researchers had already discovered much practical information about spaceflight and the problem of reentry.

As the Sputnik crisis intensified, however, the solid record of the NACA in aeronautical research and its pioneering efforts on behalf of a slow-but-sure transition to a spaceflight capability could not cancel out the worries and frustrations of the American people. The Russians had gotten a jump on us; we had somehow fallen behind; a space race had started; and our government needed to do something dramatic right now to close the gap.

In July 1958, following months of high-level meeting on the supposedly troubled state of the

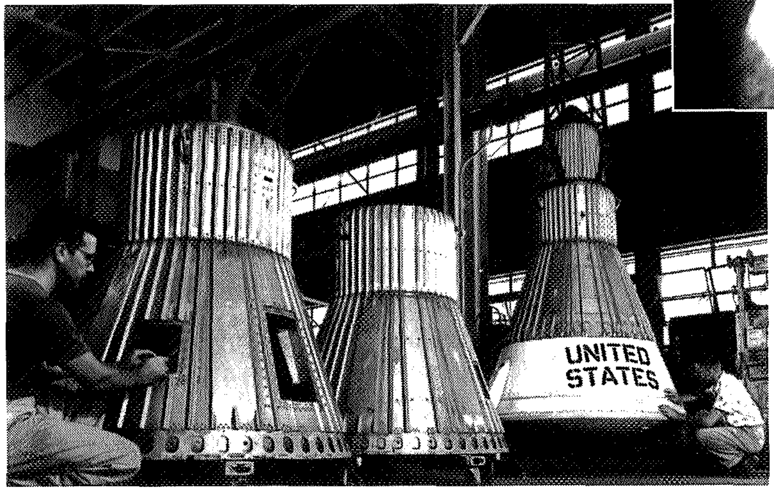


L-59-336

A NASA technician checks the Mercury capsule prior to testing in the Full-Scale Tunnel in 1959. Much of the research and development of the Mercury program was conducted at Langley. The Full-Scale Tunnel was designated a National Historic Landmark in 1985.

U.S. missile and space programs, President Dwight D. Eisenhower signed into law the National Aeronautics and Space Act. This law abolished the old NACA, turning over its staffs and laboratories, including all those at Langley, as well as some important non-NACA facilities, to a new agency, NASA.

The first "A" in NASA stood for "Aeronautics," which meant that NASA Langley would continue its outstanding tradition of aeronautical research.



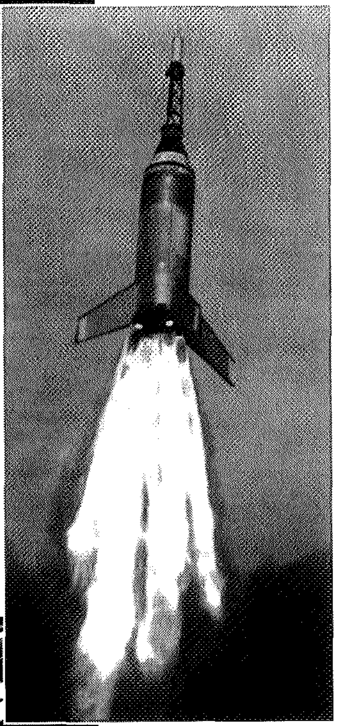
L-59-4946

The Mercury program's "Little Joe" launch vehicles under construction at Langley in 1959. Several of the capsules were launched from NASA's Wallops Station, Wallops Island, Virginia. The "Little Joe" program did much to ensure the dependability of the Mercury capsule's escape system and parachutes.

As a vital part of what came to be known as the "Space Agency," however, Langley was going to find its money reallocated, many of its efforts redirected, and much about its thinking in need of reorientation. Everyone at the laboratory was running in the "Space Race." The first major leg in that race was to get a man into orbit.

Project Mercury

In its first week of existence, NASA organized a special task force known as the Space Task Group (STG); put veteran Langley engineer Robert R. Gilruth, head of PARD, in charge of it; and based it at Langley. The job of STG was to design and implement as quickly as possible a manned satellite project.



L-59-5137

A "Little Joe" launch from Wallops Island, Virginia in January 1960.

The project's name was Mercury. In less than three years' time, it was to put the first American into space.

The STG plan was to send a small one-man spacecraft into orbit using an existing intercontinental ballistic missile, the Atlas, as the launch vehicle and a ballistic reentry shape as the crew capsule. After a few passes around the Earth, a retrorocket would be fired to slow the satellite down and thus initiate descent from orbit. Following reentry into the atmosphere, which would be accomplished safely thanks primarily to the capsule's blunt heat shield, a large parachute would deploy, carrying the capsule and its human passenger on their final approach and landing into the open sea, where they would be recovered by helicopter and brought home aboard a naval vessel.

Not only was the Space Task Group located at Langley, over half of its 350-person staff, from Gilruth on down, came from the former NACA center.

Langley itself took on much of the direct responsibility for getting Mercury off the ground. It provided extensive research and technical support for the development of "Little Joe," a test launch vehicle driven by a cluster of four Sergeant solid rockets (like those fired at Wallops Island for many years) into a single airframe. Conceived by Langley engineers Max Faget and Paul Purser even before the birth of the STG of which they became a part, "Little Joe" quickly proved to be a reliable means of testing the Mercury capsule configuration at Wallops Island before proceeding to the more expensive and difficult phases of testing at Cape Canaveral. Although the cluster of Sergeant rockets for Joe was too weak to propel the Mercury capsule into orbit (the Atlas would be required for that), testing of the little rocket did much to ensure the dependability of the Mercury capsule's escape system and drogue parachutes.

Langley engineers also designed "Big Joe," a full-scale instrumented mockup of the proposed Mercury spacecraft. This prototype, launched from Cape Canaveral on the top of an Atlas in September 1959, verified the feasibility of the Mercury capsule design.

In February 1959, NASA headquarters gave complete responsibility for planning and contracting for Mercury's worldwide tracking network, which included 18 stations around the world, to Langley.

In April 1959, the Mercury astronauts—the "Original Seven" as they came to be called—began their nationally publicized training under STG direction at Langley. While familiarizing them with the entire Mercury setup, personnel at Langley also helped the astronauts to specialize in the technical areas crucial to the overall success of the program. At the same time, they guided and monitored the astronauts' activities through the many procedure trainers and spaceflight simulators that had been built at the Center expressly for the manned space program.

Although the astronauts in training sometimes felt like guinea pigs, this was not often the case in their dealings with the Space Task Group at Langley. As the astronauts have attested, STG treated them as "active and valuable participants in the safe operation of the machine." Without a doubt, a major reason behind this respectful relationship was the years of experience that Gilruth and his staff had in dealing directly with test pilots in NACA aircraft research programs.

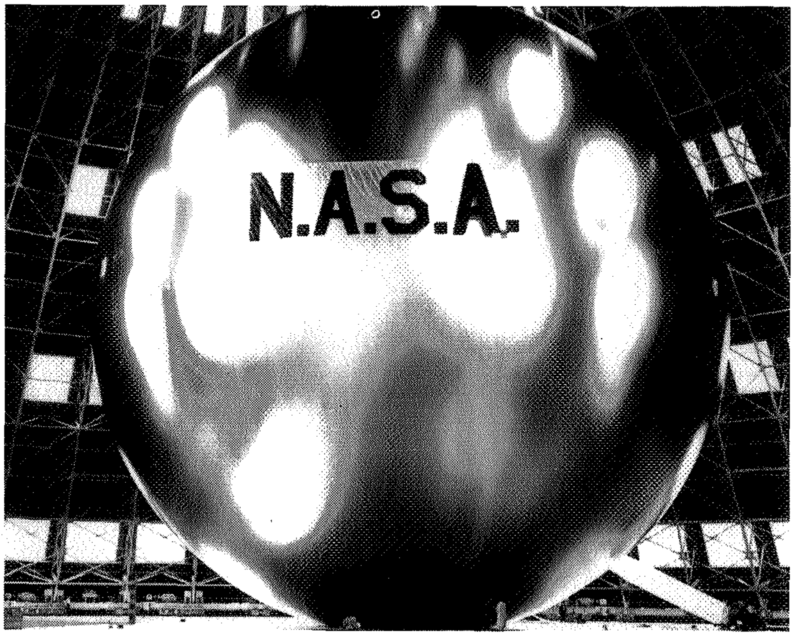
Here again, basic knowledge acquired over the years in NACA aeronautical research paved the way for a rational approach to the achievement of spaceflight. And at the same time that they were making essential contributions to the space program, researchers at NASA Langley still managed to maintain their position of overall leadership in aeronautical research.

Echo

At the same time NASA Langley was doing as much as it could to support project Mercury, some of its researchers were giving equally serious attention to unmanned satellites for scientific studies of the Earth's upper atmosphere and for the development of global communications.

Several teams of Langley researchers developed unmanned satellite concepts. One concept that came quickly to fruition was Echo. Developed under the direction of Langley scientist William J. O'Sullivan, Echo was a 100-foot-diameter balloon constructed of a very thin aluminum-coated Mylar plastic. In space it inflated automatically to a spherical shape onto which radar signals could be bounced. Folded compactly inside a metal container, Echo 1 was launched into orbit from Cape Canaveral atop a Thor-Delta rocket in August 1960.

Echo stayed in orbit for eight years, traveling more than 35,600 times around the Earth and making millions of people around the world look up into the sky in wonder at the artificial star that moved. During its billion-mile journey, the big balloon served various purposes: a test target for the development of advanced radars; a test vehicle for the development of a satellite method of performing worldwide geodetic surveys; a focal point for long-duration tests of space construction materials; and a means of providing atmospheric measurements on the border of space.



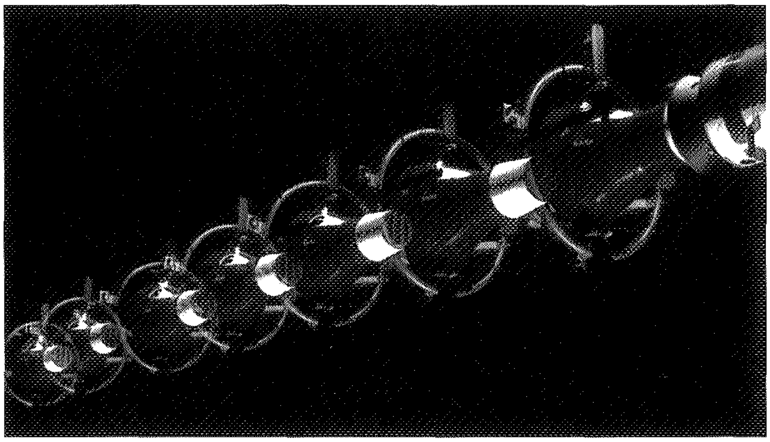
L-61-4597

Conceived at Langley, the Echo communications satellite, designed to reflect radio and radar signals, undergoes an inflation test in 1959. Echo was the world's first passive communications satellite.

So among Langley's many contributions to spaceflight should be counted the world's first passive reflector communications satellite.

Destination Moon

Project Mercury grew into Project Apollo—by way of Project Gemini. This happened initially without much fanfare, because the first announced goal of Apollo was simply to sustain an orbit around the Earth, or perhaps the moon, with a multi-man crew. As always, Langley Research Center was ready to do what it could to help.



L-64-1609
Rendezvous and docking in space were tested and practiced at Langley with free-moving vehicles suspended on cables with the Rendezvous Docking Simulator, now a National Historic Landmark. Here it is being used to simulate conditions to be found during the Gemini-Agena Missions.

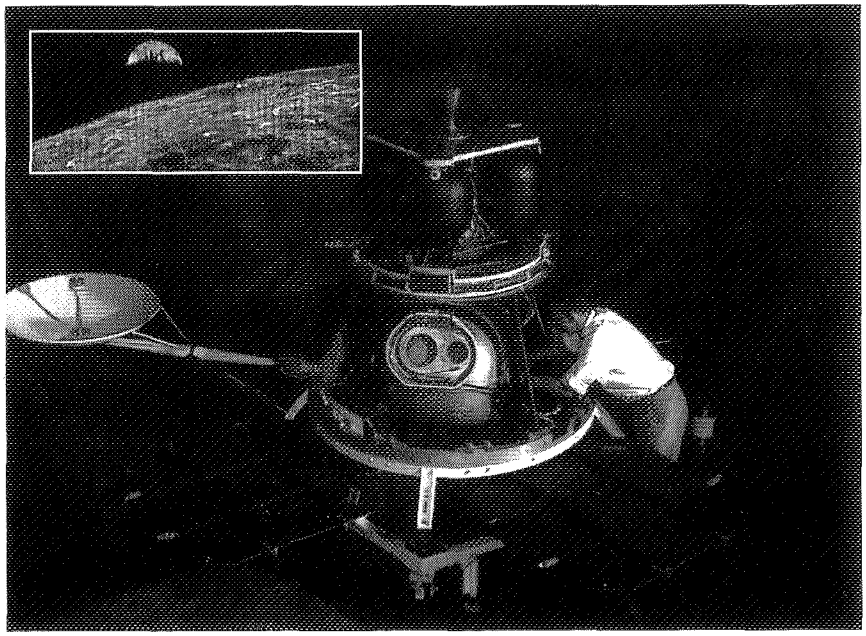
On May 25, 1961, however, the plan for Apollo changed in an incredibly big way: In a speech to Congress, President John F. Kennedy committed the nation to a manned lunar landing "before the decade is out." Apollo was the vehicle.

Answering President Kennedy's challenge and landing men on the moon by 1969 required the most sudden burst of technological creativity and the largest commitment of resources ($24 billion) ever made by the nation in peacetime. At its peak the Apollo program employed an estimated 400,000 Americans and required the support of some 20,000 industrial firms and universities. As JFK had said, "it will not be one man going to the moon—it will be an entire nation. For all of us must work to put him there."

NASA Langley participated more than most in the achievement of the lunar objective. It helped to establish and improve the basic concepts and fundamentals of both the Apollo program and its necessary antecedent, Project Gemini. (After thinking through the lunar mission for several months, NASA created Gemini in order to establish the feasibility of rendezvous and docking in space before having to face them in faraway lunar orbit.) In the Center's wind tunnels, researchers studied the aerodynamic integrity of the Saturn-Apollo launch combination. Under the title of Project Fire, they investigated reentry heating and its potentially fatal effects on a returning spacecraft. They also played a major role in the training programs that prepared the astronauts for rendezvous and docking and for the actual landing of a manned spacecraft and astronaut locomotion activities on the moon. In the mid-1960s they also managed the very important Lunar Orbiter Project that made systematic photographic maps of the lunar landing sites.

(below) A preparatory examination of the Lunar Orbiter spacecraft. The craft photographically mapped 99 percent of the moon's surface.

L-66-6399
(inset) Our first view of the Earth taken by a spacecraft from the vicinity of the moon. The photo was transmitted to Earth by the United States' Lunar Orbiter I and received at the NASA tracking station near Madrid, Spain. The crescent Earth was photographed August 23, 1966 when the spacecraft was on its 16th orbit and just about to pass behind the moon.



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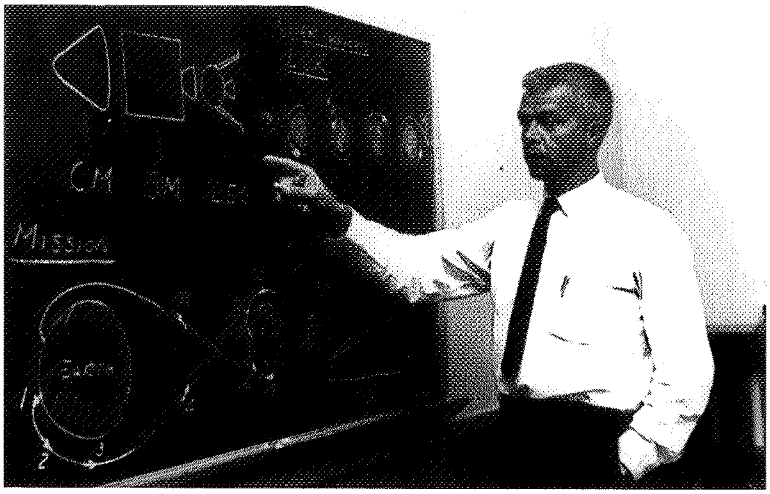


62-5848

John C. Houbolt explains the Lunar Orbit Rendezvous (LOR) concept. Without this successful mission concept, the United States may have still landed men on the moon, but it probably would not have happened by the end of the 1960s as directed by President John F. Kennedy. The basic premise of LOR was to fire an assembly of three spacecraft into Earth orbit on top of a single powerful rocket.

Langley's most fundamental contribution to Apollo, however, was its development of the lunar-orbit rendezvous (LOR) concept. On it, the success of Apollo absolutely depended.

The brainchild of a few true believers who had been experimenting with the idea since 1959, the basic premise of LOR was to fire an assembly of three spacecraft into Earth orbit on top of a single powerful rocket (which turned out to be Wernher von Braun's Saturn V). This assembly would include (1) a mother ship or command module, (2) a service module containing the fuel cells, attitude control system, and main engines, and (3) a small lunar lander. In Earth orbit, the last stage of the rocket would fire, boosting the combined Apollo spacecraft on to its flight trajectory to the moon. In lunar orbit, two crew members would don space suits and climb into the lunar lander and take it down to the surface. The third crew member would maintain a lonely vigil in lunar orbit inside the mother ship. After exploring, the top half of the lunar excursion module (LEM) would rocket back up and re-dock with the command module. The LEM would then be discarded to the vastness of space, and the three astronauts in their command ship would head for home.

The inherent complications and grave dangers of rendezvous in distant lunar orbit, where nothing could be done to save the astronauts if there was trouble, worried leaders of the Apollo program greatly. After months of debate, however, NASA endorsed the bold plan of the Langley engineers. The leadership did so because LOR, unlike the other two options (direct-ascent and Earth-orbit rendezvous), offered a real chance of achieving a manned lunar landing by 1969.

Even before its controversial mission concept had been selected by NASA headquarters as the mission mode for Apollo, Langley had made several successful simulated studies of a manned lunar landing using LOR. After LOR was formally chosen in July 1962, researchers at the Center constructed major training facilities, such as the Rendezvous and Docking Simulator and the Lunar Landing Research Facility, to make sure that the Apollo astronauts mastered the necessary piloting techniques and procedures long before they blasted off.

The LOR concept, and the training it required at Langley and elsewhere, worked out beautifully. On July 20, 1969, Apollo 11 astronauts Neil Armstrong and Buzz Aldrin in the lunar module "Eagle" gingerly made their way down to the Sea of Tranquility, becoming the first men on the moon. Circling above, in lunar orbit, was astronaut Michael Collins in the command module "Columbia."

L-70-2208

Alan Shepard during tests with the full-scale Lunar Excursion Module Simulator. The simulator made it possible for Apollo astronauts to practice landing on the lunar surface and gave them the opportunity to study and overcome problems that could have occurred during the final 150-foot descent to the surface of the moon.

Kennedy's lunar objective had been met — just barely — and it had been done according to the LOR plan that Langley engineers had proposed and championed through strong opposition. Six more flights followed to the moon in the next two and a half years, the last one—Apollo 17—taking place in December 1972. Each mission visited a different spot but took a path to and from the moon that was a carbon copy of Apollo 11. Each was done via LOR.

Skylab

From Apollo technology there was one major spinoff program to which NASA Langley made several significant contributions; this was Skylab.

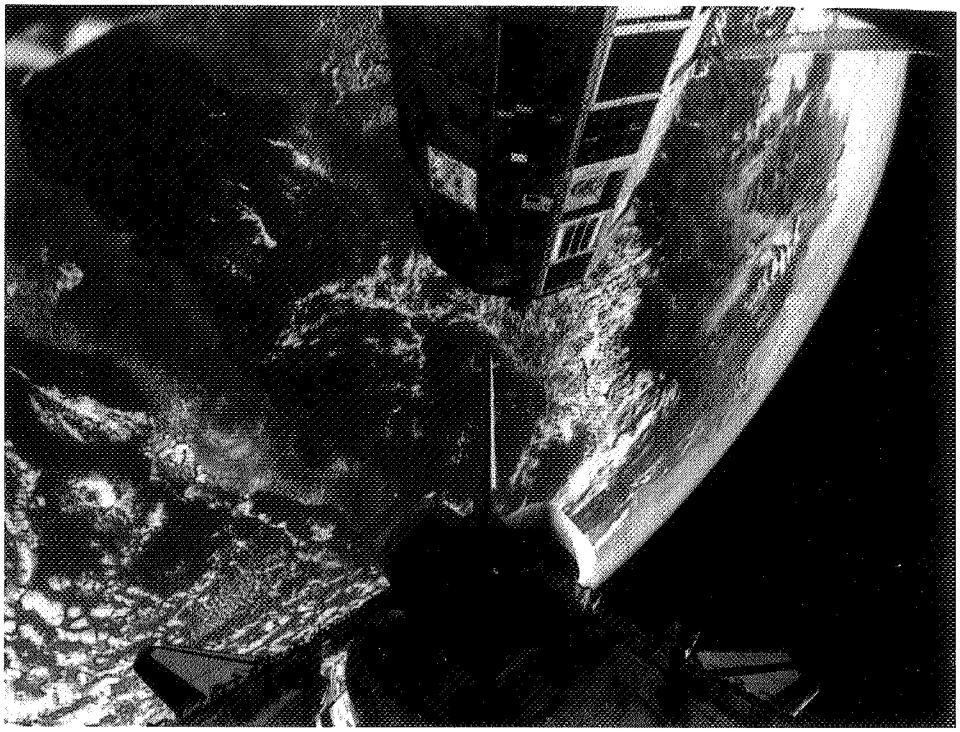
A much overlooked achievement of the early 1970s, Skylab was in essence our country's first operational space station. NASA built it inside the third stage of a Saturn rocket, outfitted as a laboratory on the ground, and then launched it into Earth orbit. Skylab was inhabited for weeks at a time in 1973 and 1974 by three different teams of separately—launched astronauts who had docked with it inside an Apollo spacecraft.

Inside Skylab, which was about the size of a three-bedroom house, the astronauts conducted fundamental research in astronomy, biology, and medicine, while NASA monitored and tested their performance in long-duration flights lasting as long as 84 days. Even though the program lasted for less than a year, a great deal was learned about what it would be like for humans to live and work in weightlessness for long stretches of time inside a space habitat. Such physiological and psychological information about space travelers will be vital if humankind ever attempts interplanetary voyages.

Several experiments conducted in Skylab were devised at Langley. Researchers at the Center also helped to work up the essential sunshade devices that not only kept the Skylab's interior cool but protected its inhabitants from harmful solar radiation and high-energy cosmic rays.

Space Station

NASA Langley had worked on various space station concepts long before Skylab—-or even before Apollo. In fact, during the early 1960s, when many experts felt that an Earth-orbiting station would be necessary as a relay base for lunar missions, Langley's designs led the way in NASA for planning of a manned orbiting laboratory.


L-92-1253

LDEF carrried 57 experiments into low-Earth orbit for six years. On board were more than 10,000 items to test the effects of long-term space exposure on spacecraft materials, components and systems. Pictured is its 1990 retrieval by the Space Shuttle Columbia.

Although this lead was later taken over by Houston and Huntsville, Langley over the years has continued to probe the many technical challenges of designing, building, and operating an effective multi-purpose laboratory in space. Today this involvement includes substantial work in support of NASA's plans for Space Station Freedom. Langley staff members are deeply involved in researching the technologies, materials, and automated construction processes that make such large structures in space possible.

One step in this direction was the deployment and retrieval of Langley's Long Duration Exposure Facility (LDEF), which was conceived, designed and developed at Langley. The bus sized satellite carried 57 experiments into low-Earth orbit for six years. On board were more than 10,000 items to test the effects of long-term space exposure on spacecraft materials, components and systems. The wealth of information colected during its journey will be invaluable for the design of future spacecraft.

Space Shuttle

With its tradition of research into the performance of winged flying vehicles and its pioneering work on hypersonic gliders, the X-15, and other types of "space planes," it should be no surprise that Langley made vital contributions to NASA's Space Shuttle program. Much of the basic aerodynamic testing of the Space Shuttle was done in Langley's wind tunnels.

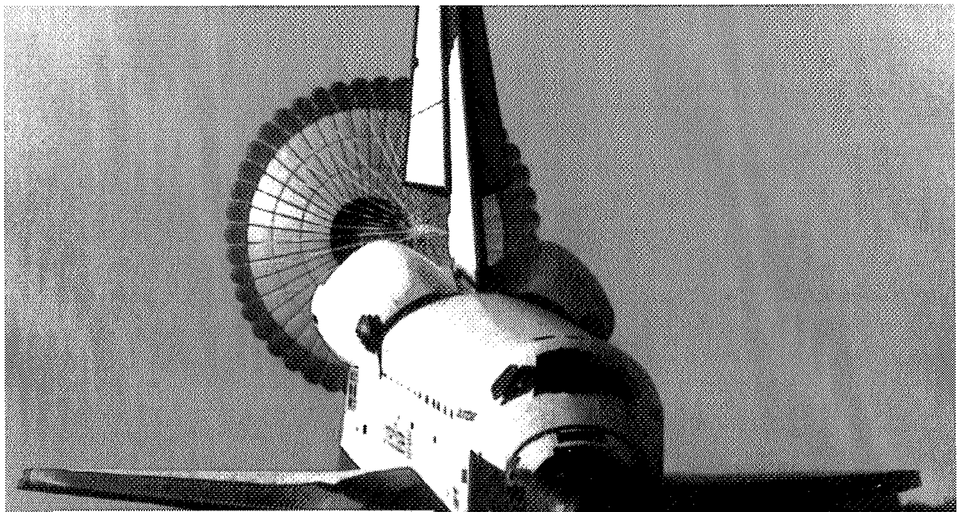
The problems facing a hybrid reusable vehicle that flies into, through, and back from space, from blastoff to a landing on a runway, are unusually extreme—to say the least. During any mission, the Shuttle must pass through three distinctly different flight regimes: hypersonic, supersonic, and subsonic. Over the years Langley engineers pioneered research in each one of these speed regimes, and knew that each regime by itself posed difficult problems. Together, these problems made the Shuttle program into one of the biggest challenges Langley's wind-tunnel complex ever faced. Just to complete the essential work, it took NASA Langley many thousands of hours of wind-tunnel testing over a period of several years.

Even today Langley engineers continue to explore the performance of the Shuttle. Among a number of program support activities, there has been a focus on further testing of the Shuttle's landing and crew emergency escape systems, reentry heating conditions, and overall materials.

Future Spaceflight Vehicles

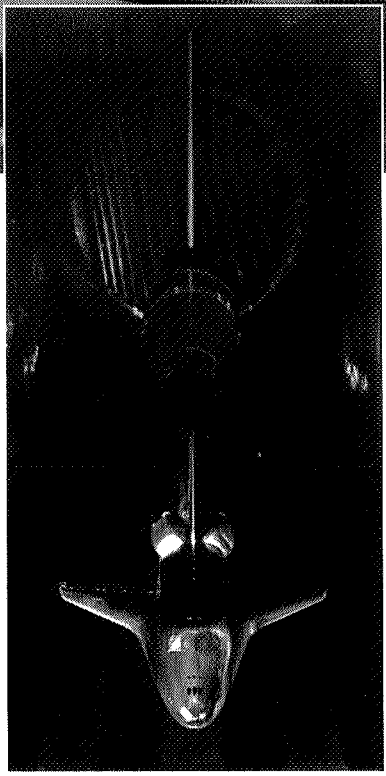
While continuing to support the Shuttle program, NASA Langley also has been exploring the feasibility of a number of new type spaceflight vehicles for future U.S. operations.

Hypersonic research has been a Langley forte for over 40 years, and it will continue to be of fundamental importance to its national mission for many years to come. In 1987 NASA selected Langley as the lead center in charge of studying the technologies needed by a hypersonic aerospace plane. The transatmospheric vehicle that has been conceived in theory would be capable of accelerating to speeds in excess of twenty times the speed of sound, jumping into space, and traveling between any two points on the globe in two hours or less.



KSC-92-PC-1461

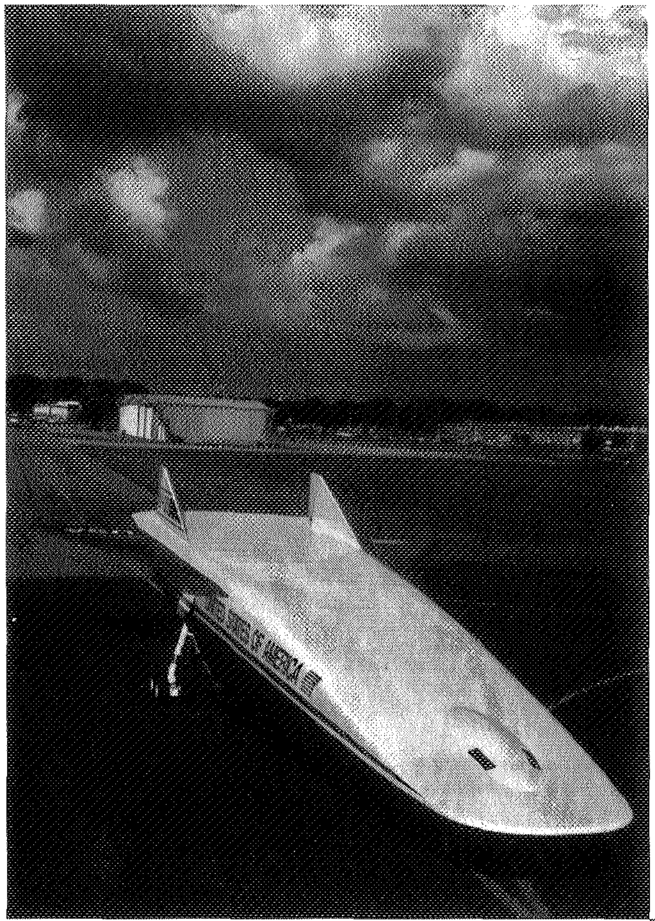
(above) The Space Shuttle Columbia and her crew of seven touches down at Kennedy Space Center in July 1992. Its return marks the successful completion of mission STS-50, the longest flight in Space Shuttle history–13 days, 19 hours, 30 minutes and four seconds.



L-85-2,800

(left) "Flying qualities" of the the Space Shuttle, important to a successful atmospheric reentry and landing, are tested here in the National Transonic tunnel.

The development of the aerospace plane will depend, however, not only on a military mission or economical use for such a vehicle, but also on yet-to-be found solutions to a web of obstinate aerothermodynamic and propulsion problems.



92-06707

The 50-foot-long National Aero-Space Plane mockup during a tour of the country in 1992. Students at Mississippi State University won the opportunity to build the one-third scale mockup in a nationwide competition. Langley serves as NASA's technology lead for the program.

Specifically, it will hinge on the feasibility of a powerful new air-breathing propulsion system known as a scramjet. This unique engine, a supersonic combustion ramjet, would breathe air up to the outer reaches of the atmosphere and then use rockets to maneuver in space.

In the last few years, research at Langley has gone a long way toward proving the value not only of the scramjet but also of an integrated aerospace plane design. A recent upgrading of its 8-Foot High-Temperature Tunnel gives the Center one of the premier scramjet testing facilities in the world.

To complement the Space Shuttle system and provide assured manned access to space for the next generation of space programs, Langley has conceived the HL-20 lifting body "space taxi." This system was designed primarily to change Space Station Freedom crews.

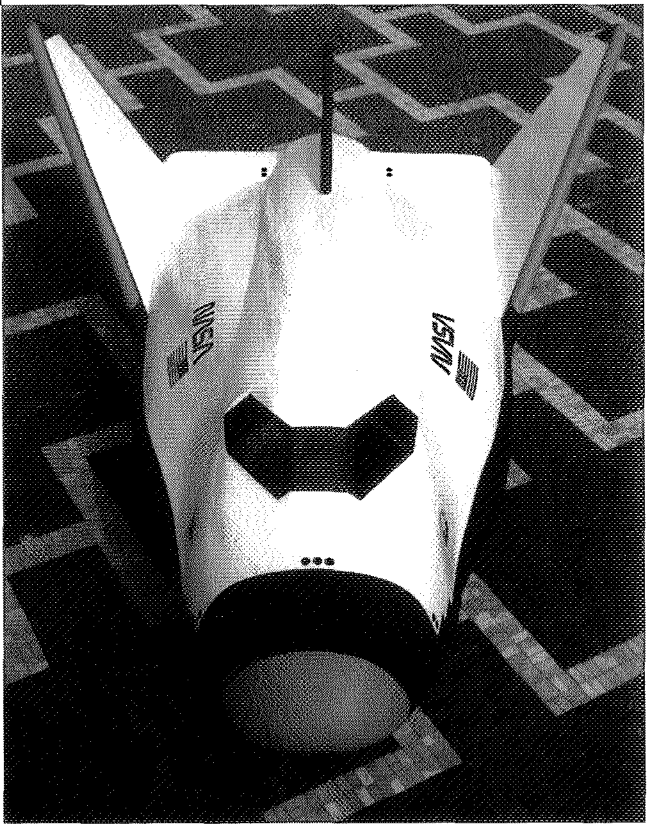
Another current thrust for future spaceflight at Langley is research into the potential of "aeroassist" or "aerobraking" technology. The common means of slowing down a spacecraft during atmospheric reentry ever since the flights of the blunt-bodied Mercury capsule, aerobraking technology is important to the future of the space program because it is a way that could enable a spaceship to decelerate within a planetary atmosphere without using up its precious fuel supply.

NASA believes aerobraking technology has important applications for a future class of modular "transfer vehicles" that might take payloads or crews from a spaceport in low Earth orbit to the moon, Mars, or other destinations in the inner solar system.

Viking to Mars

A mission that has always excited dreamers is a manned landing on the intriguing planet Mars. According to many spaceflight enthusiasts, including the members of the 1985 National Commission on Space, Mars is the next grand destination for human exploration.

NASA Langley has more than a passing acquaintance with the Red Planet. For several years it was the home of the Viking program that in 1976 sent four unmanned spacecraft to Mars: two orbiters that took photographs and served as a communications relay, and two landers that descended to the Martian surface and probed in



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The HL-20 "space taxi" was conceived to complement the Space Shuttle, designed to change the Space Station Freedom crews and transport small payloads to the station.

various ways for evidence of rudimentary life forms and for conditions that might have once given birth to some.

As far as the Viking's biological instruments and other elaborate probes and sensors could tell, nothing presently lives on Mars. The evidence also suggested, however, that things might have been very different in the past.

The successful missions of four spacecraft to Mars—some 65,000,000 kilometers away—must be rated as one of the greatest technological triumphs of our time. In some ways, the achievement surpasses even the Apollo landings on the moon.

Without a doubt, Viking is one of Langley's greatest achievements and one of its most outstanding contributions to space exploration.

Mission to Planet Earth

At present NASA Langley is also leading the way for much of the basic science that might be done as part of what former NASA astronaut Sally Ride has called "Mission to Planet Earth." The goal of this critical mission would be nothing less than the continued good health of our good Mother Earth.

The key to this mission is the use of satellites and other space technologies as a means of keeping a close eye on the ozone layer and other changes in our precious global biosphere. Over time these changes, though subtle, can have a very damaging or even catastrophic impact on life here on Earth.

Summary

Through hard work, inspiration, and imagination, a basic knowledge of aeronautical problems has evolved over the years at NASA Langley Research Center into opportunities for flight and the exploration of space.

Langley may not have the launch pads, the mission control rooms, or the spacecraft landing sites, but it possesses the essential tools of aerospace research. Without those tools and the talented people who build, use, and learn from them, no venture into space could ever be attempted safely.

"NASA Langley Research Center's Contributions to Spaceflight" was prepared by the NASA Langley Research Center Office of Public Affairs with the assistance of Dr. James R. Hansen, author of ***Engineer in Charge, A History of the Langley Aeronautical Laboratory 1917-1958.***

1917 - 1992
75 Years
NACA
NASA
Langley Research Center

ISY

National Aeronautics and
Space Administration

Langley Research Center

NASA Facts

National Aeronautics and
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Langley Research Center
Hampton, Virginia 23681-0001
804 864-3293

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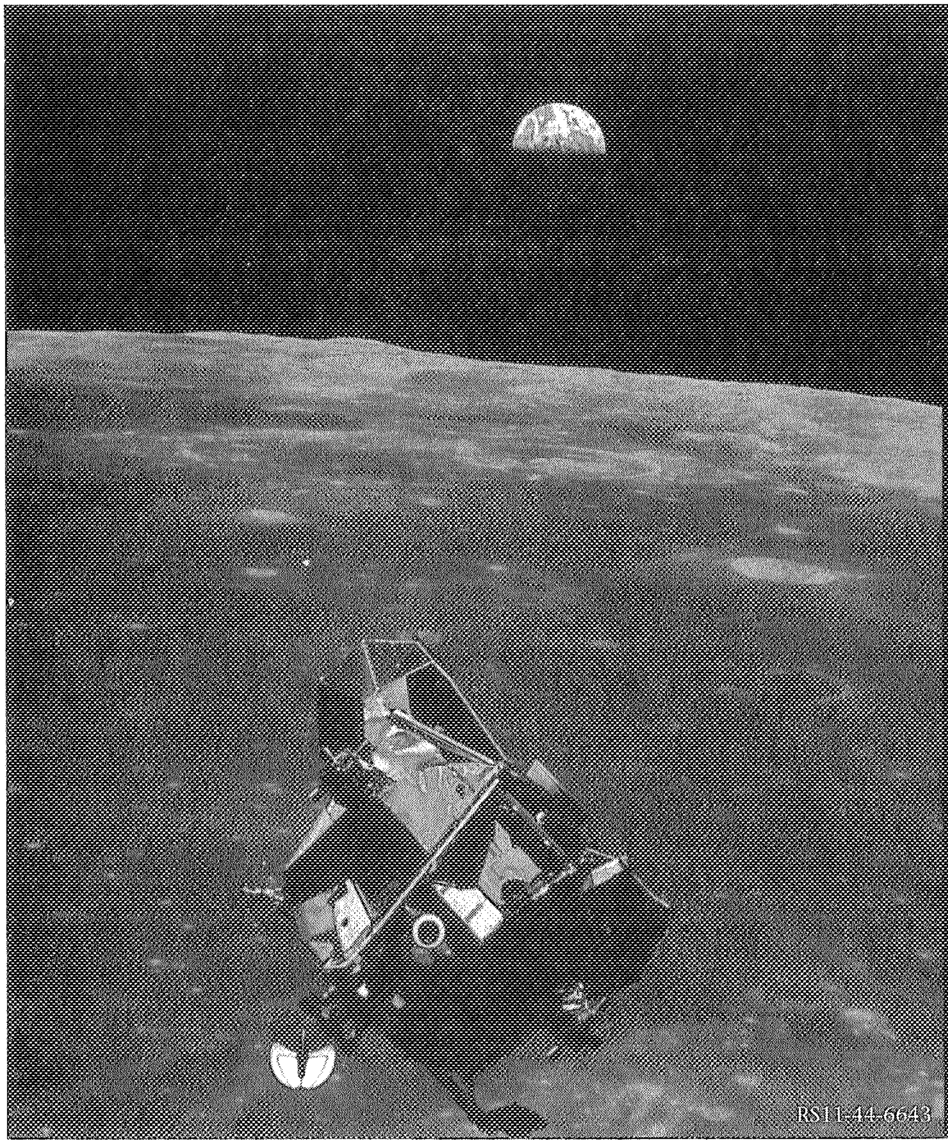
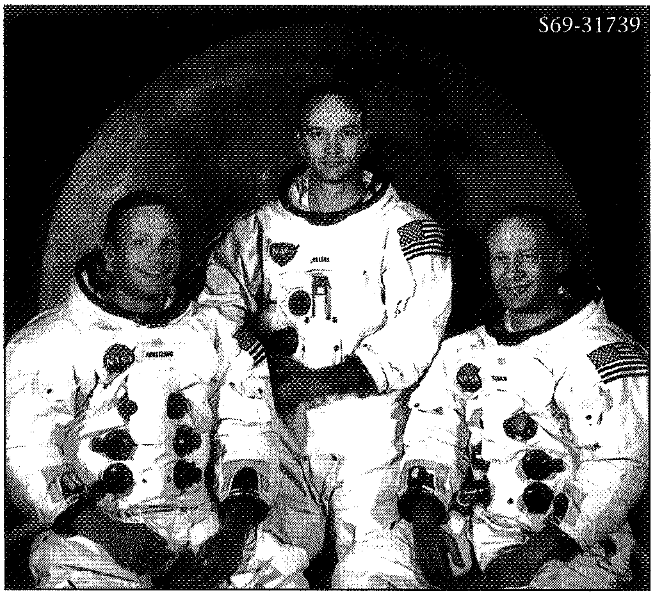
The rendezvous that was almost missed:
Lunar Orbit Rendezvous and the Apollo Program



In the opinion of many space historians, NASA Langley's most important contribution to the Apollo Program was its development of the lunar-orbit rendezvous (LOR) concept. The brainchild of a few true believers at Langley, LOR's basic premise was to fire an assembly of three spacecraft into Earth orbit on top of a single powerful rocket.

Pictured is the Apollo 11 lunar module during rendezvous in lunar orbit with the command module. If rendezvous around the moon had failed, the astronauts would have been too far away to have been saved. The large dark colored area in the background is Smith's Sea. The Earth rises above the lunar horizon.



Astronauts Edwin "Buzz" Aldrin, Neil A. Armstrong and Michael Collins after their selection to become the prime crew of the Apollo 11 lunar landing mission.

More than twenty years have passed since July 20, 1969, when the lunar module "Eagle" with Apollo 11 astronauts Neil Armstrong and Buzz Aldrin aboard gingerly made its way down to the Sea of Tranquility, landing men on the moon for the first time.

Thousands of people and organizations in many different places played key roles in this "giant leap for mankind." As President Kennedy stated in the May 1961 speech to Congress in which he announced the nation's commitment to the lunar challenge, "It will not be one man going to the moon—it will be an entire nation. For all of us must work to put him there."

One place that was fortunate to participate more than a little in the achievement of the lunar objective was the NASA Langley Research Center in Hampton, Va., the nation's oldest civilian aeronautics laboratory and home of the Space Task Group that conceived and directed Project Mercury, America's first man-in-space program.

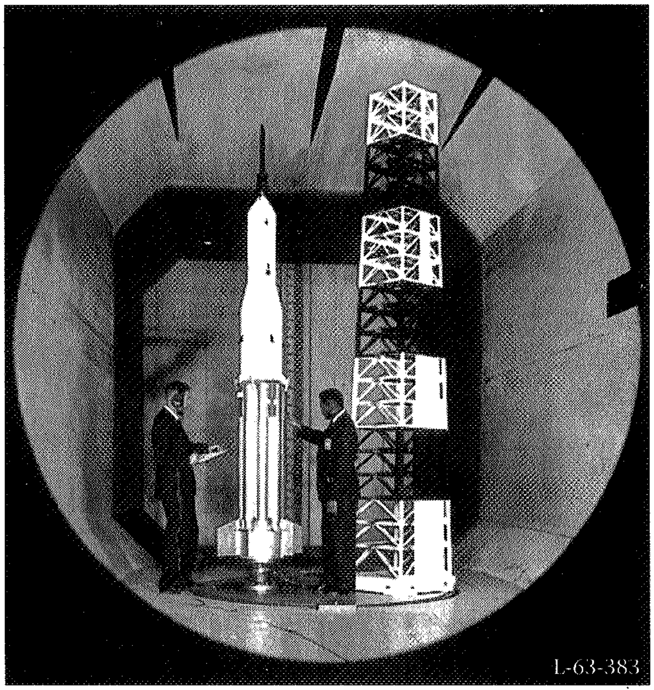
NASA Langley helped to establish many of the basic fundamentals and mission concepts central to the success of the Apollo program. In the laboratory's unique complex of wind tunnels, researchers studied the aerodynamic integrity of the Saturn-Apollo launch configuration and the problem of aerodynamic heating during the reentry of the Apollo command module into the Earth's atmosphere. Langley staff members and test facilities also played a major role in the training programs necessary to prepare NASA's astronauts for landing on the moon and moving around on its surface.

In the opinion of many space historians, however, Langley's most important contribution to Apollo was its development of the lunar-orbit rendezvous concept.

President John F. Kennedy's decision in 1961 to land a man on the moon "before the decade is out" meant that NASA had to move quickly to find the best method of accomplishing the journey. NASA gave serious consideration to three options: Initially, direct ascent; then, Earth-orbit rendezvous (EOR), and, finally, a darkhorse candidate, lunar-orbit rendezvous (LOR).

Direct ascent was basically the method that had been pictured in science fiction novels and Hollywood movies. A massive rocket the size of a battleship would be fired directly to the moon, land and then blast off for home directly from the lunar surface. The trip would be like that of a chartered bus, moving from point A to point B and back to A again in one brute of a vehicle.

Strong feelings existed within NASA in favor of direct ascent, largely because it meant the development of a proposed giant booster named the Nova. After the engineers made their calculations, however, NASA realized that any single big rocket that had to carry and lift all the fuel necessary for leaving the Earth's gravity, braking against the moon's gravity as well as leaving it, and braking back down into the Earth's gravity again, was clearly not a



Extensive research into the aerodynamic forces affecting the Saturn-Apollo launch configuration was performed in Langley wind tunnels. Here, researchers study the effects of wind on the Saturn V rocket and escape tower.

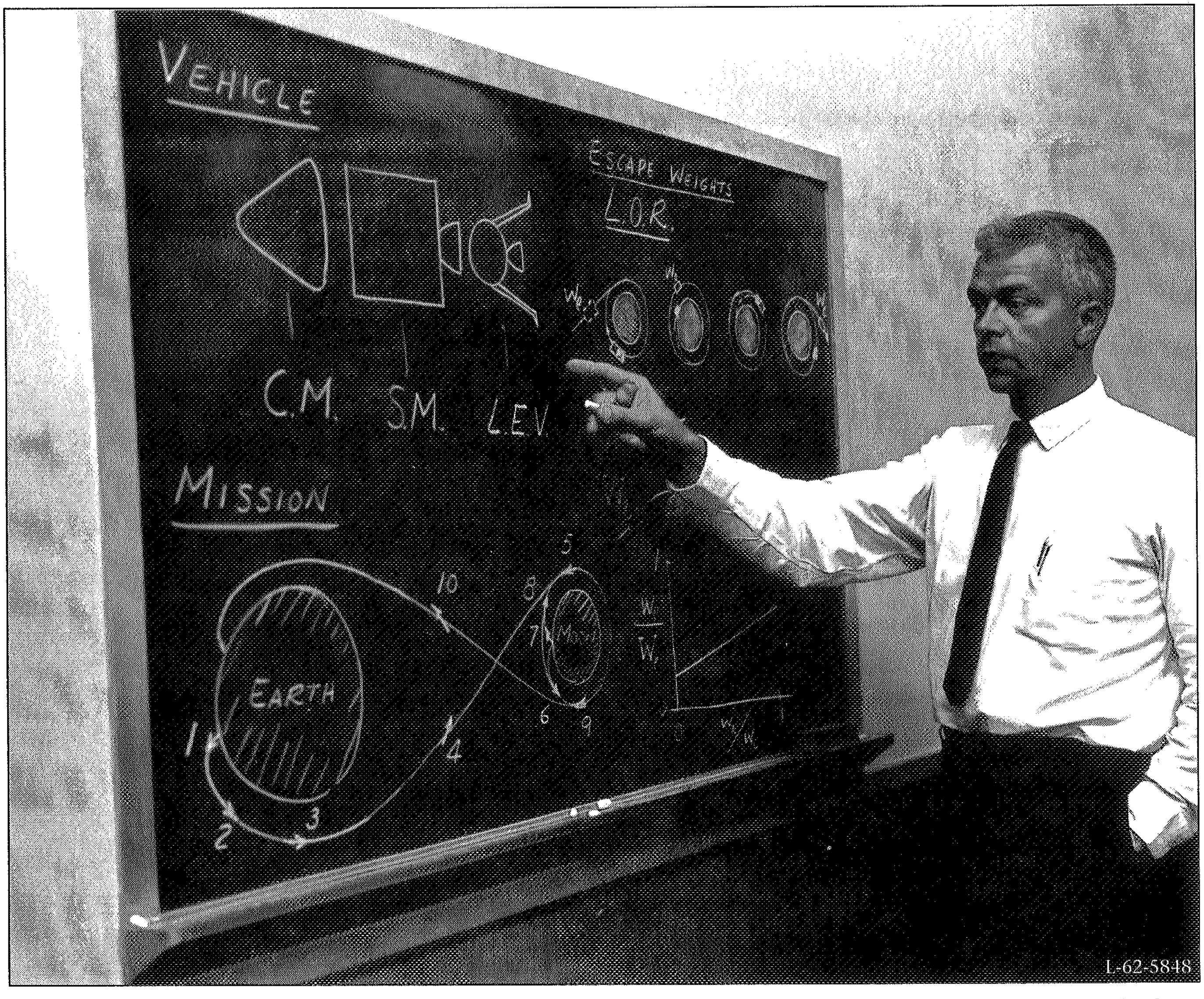
realistic option—especially if the mission was to be accomplished anywhere close to President Kennedy's timetable. The development of a rocket that mammoth would just take too long, and the expense would be enormous.

The demise of direct ascent led to a scrupulous evaluation of the second option: Earth-orbit rendezvous. The main idea of EOR was to launch two pieces into space independently using advanced Saturn rockets that were then in development; have the two pieces rendezvous and dock in Earth orbit; assemble, fuel, and detach a lunar mission vehicle from the modules that had joined up; and then proceed with that bolstered ship, exactly as in the direct flight mode, to the moon and back to Earth orbit. The advantage of EOR was that it required a pair of less powerful rockets that were already nearing the end of their development.

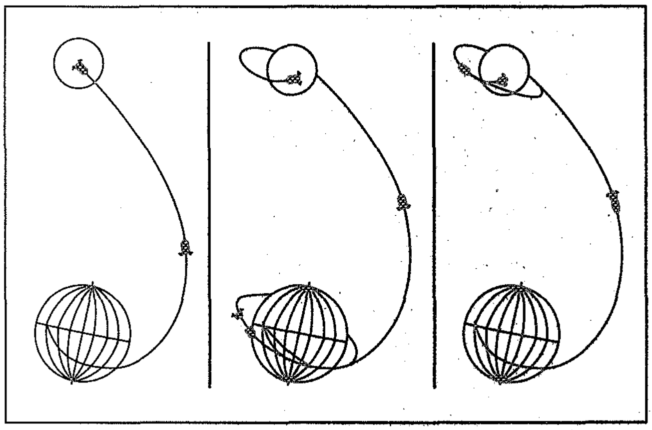
EOR enjoyed strong support inside of NASA, especially among those who recognized that selection of EOR as the mode for the Apollo mission would require the virtual construction of a space station, a platform in Earth orbit that could have many other uses, scientific and otherwise, beyond Apollo. For this reason, space station advocates like Dr. Wernher Von Braun and his associates at NASA's Marshall Space Flight Center in Huntsville, Alabama, favored EOR.

In the end NASA selected neither of the first two options: instead, it selected the third: lunar-orbit rendezvous.

The brainchild of a few true believers at the Langley Research Center who had been experimenting with the idea since 1959, the basic premise of LOR was to fire an assembly of three spacecraft into Earth orbit on top of a single powerful (three-stage) rocket.



Dr. John C. Houbolt explains the lunar orbit rendezvous concept that, in the opinion of many historians, was chief among the reasons why the U.S., in less than a decade, managed humankind's first extraterrestrial excursion.

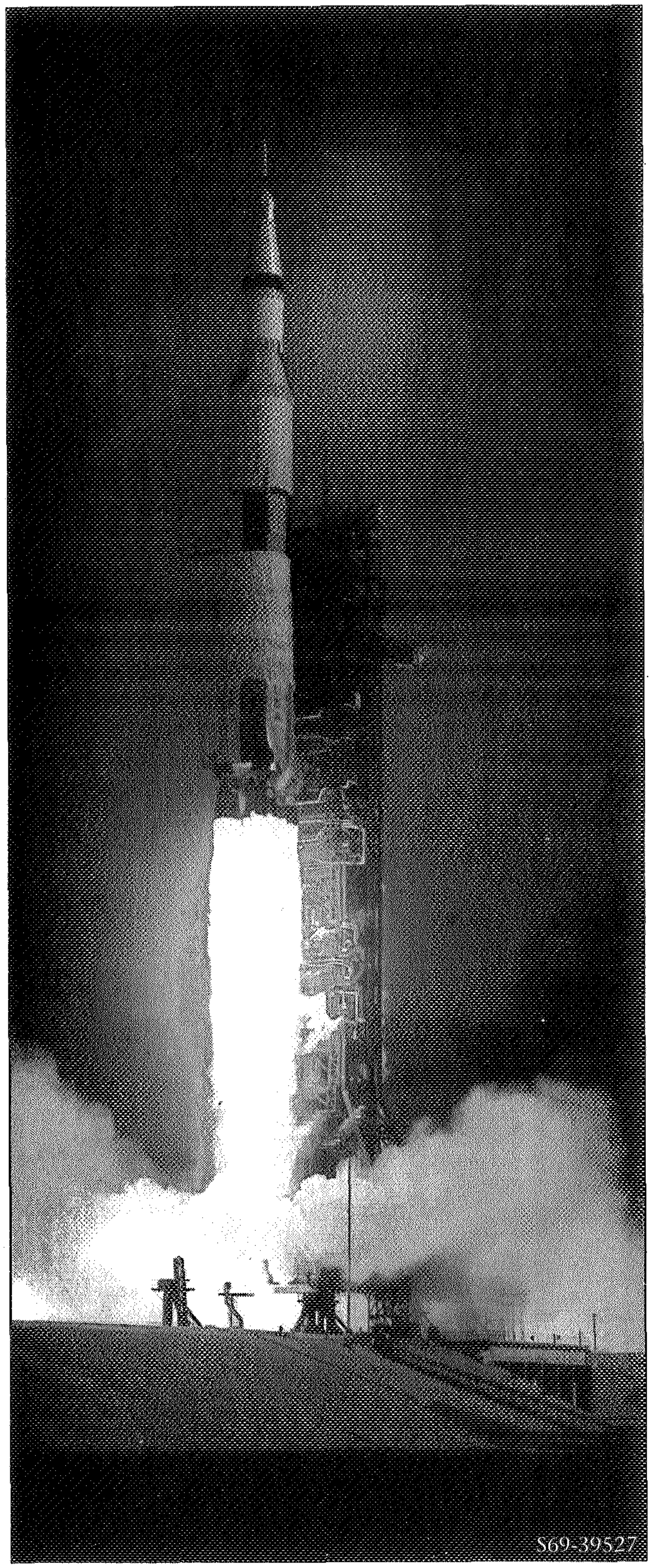


President John F. Kennedy's decision in 1961 to land a man on the moon "before the decade is out" meant that NASA had to move quickly to find the best method of accomplishing the journey. NASA gave serious consideration to three options: initially, direct ascent; then Earth-orbit rendezvous (EOR), and, finally, a darkhorse candidate, lunar-orbit rendezvous (LOR).

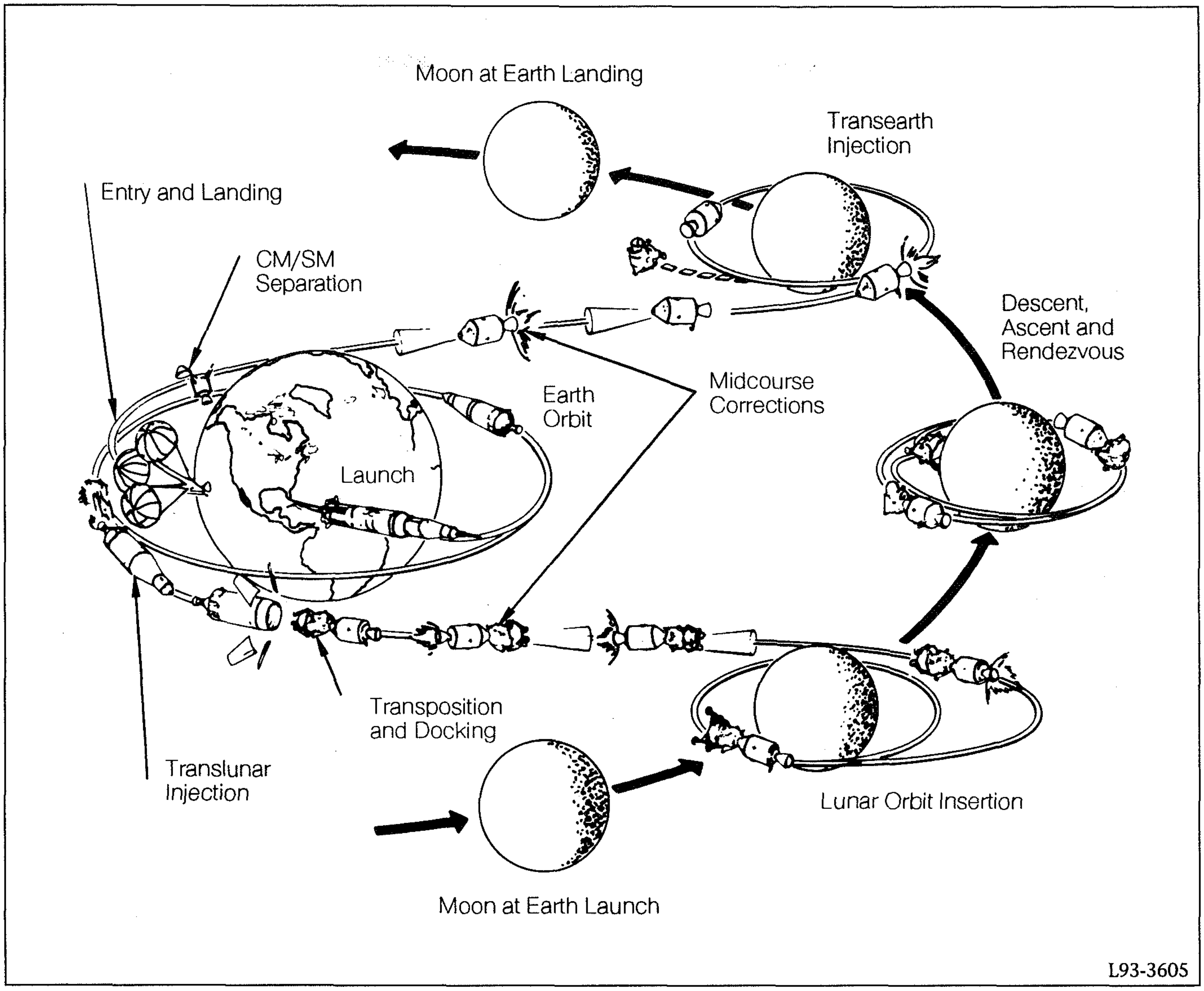
This assembly included: One, a mother ship or command module; two, a service module containing the fuel cells, attitude control system, and main propulsion system; and three, a small lunar lander or excursion module. Once in Earth orbit, the last stage of the rocket would fire, boosting the Apollo spacecraft with its crew of three men into its flight trajectory to the moon. Reaching lunar orbit, two of the crew members would don space suits and climb into the lunar excursion module (or LEM), detach it from the mother ship, and take it down to the lunar surface. The third crew member would remain in the command module, maintaining a lonely vigil in lunar orbit. If all went well, the top half of the LEM would rocket back up, using the ascent engine provided, and re-dock with the command module. The lander would then be discarded to the vast darkness of space, or crashed onto the moon (as was done in later Apollo missions for seismic experiments), and the three astronauts in their command ship would head for home.

Although the basics of the LOR concept had been expressed as early as 1923 by German rocket pioneer Herman Oberth, no one had recognized the fundamental significance of LOR until two separate groups of Langley researchers in 1959, not long after Sputnik and the creation of NASA, quietly began to think about the potential of LOR for the budding American space program.

One of these groups was the Lunar Mission Steering Group headed by Clinton E. Brown, head of the Theoretical Mechanics Division. The other was the Rendezvous Committee headed by Dr. John C. Houbolt, then the assistant chief of the Dynamics



The basic premise of LOR was to fire an assembly of three spacecraft into Earth orbit on top of a single powerful rocket (Saturn V). With the Apollo spacecraft, the Saturn V stood 363 feet tall. Pictured is the July 16, 1969 launch of Apollo 11, the first mission to land men on the moon.



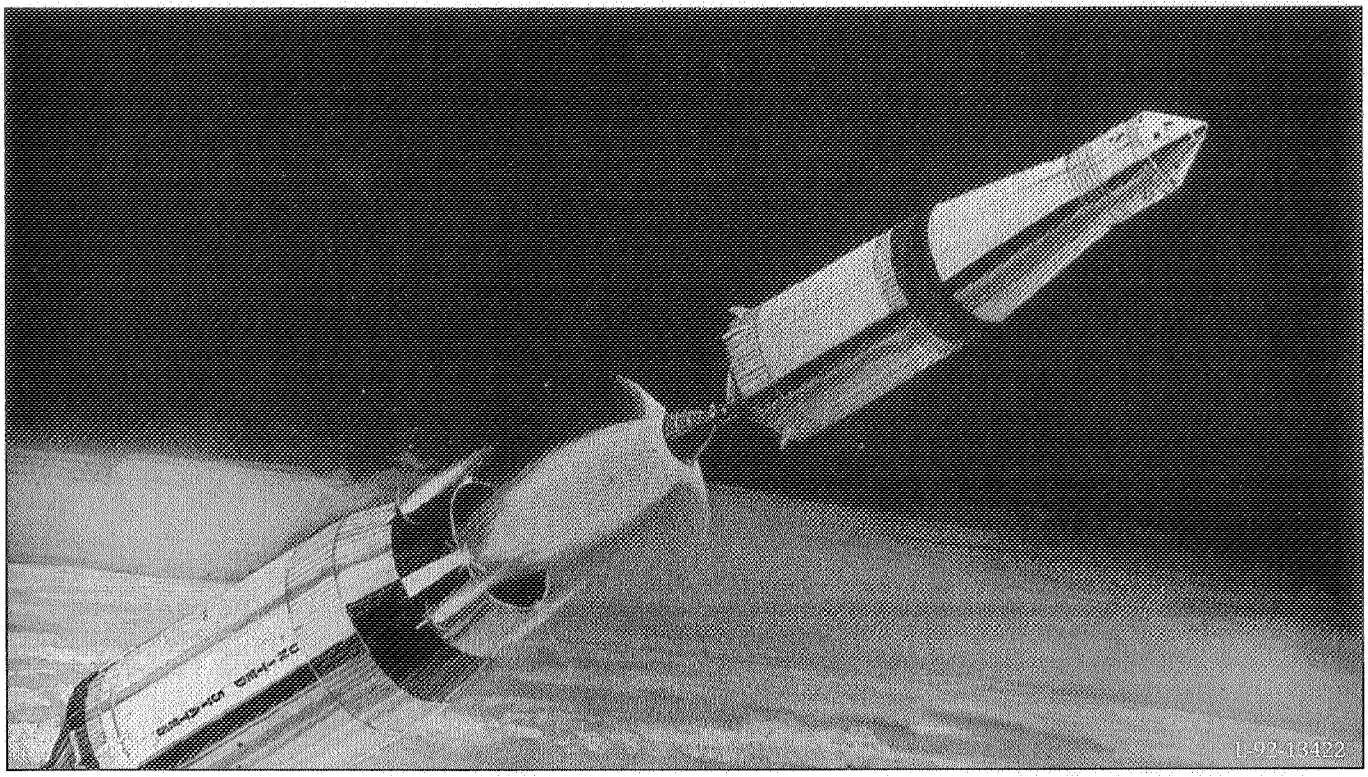
A stage-by-stage lunar mission profile.

Load Division. Brainstorming by these two Langley groups, done at first independently, led to an intensive analysis of what were then thought to be two distinct subjects: one, the mechanics of a moon trip and, two, the role of rendezvous in the operations of an Earth-orbiting space station. The idea of putting the two analyses together then led a few creative minds within the Langley study groups to consider the advantages of LOR for a manned lunar mission.

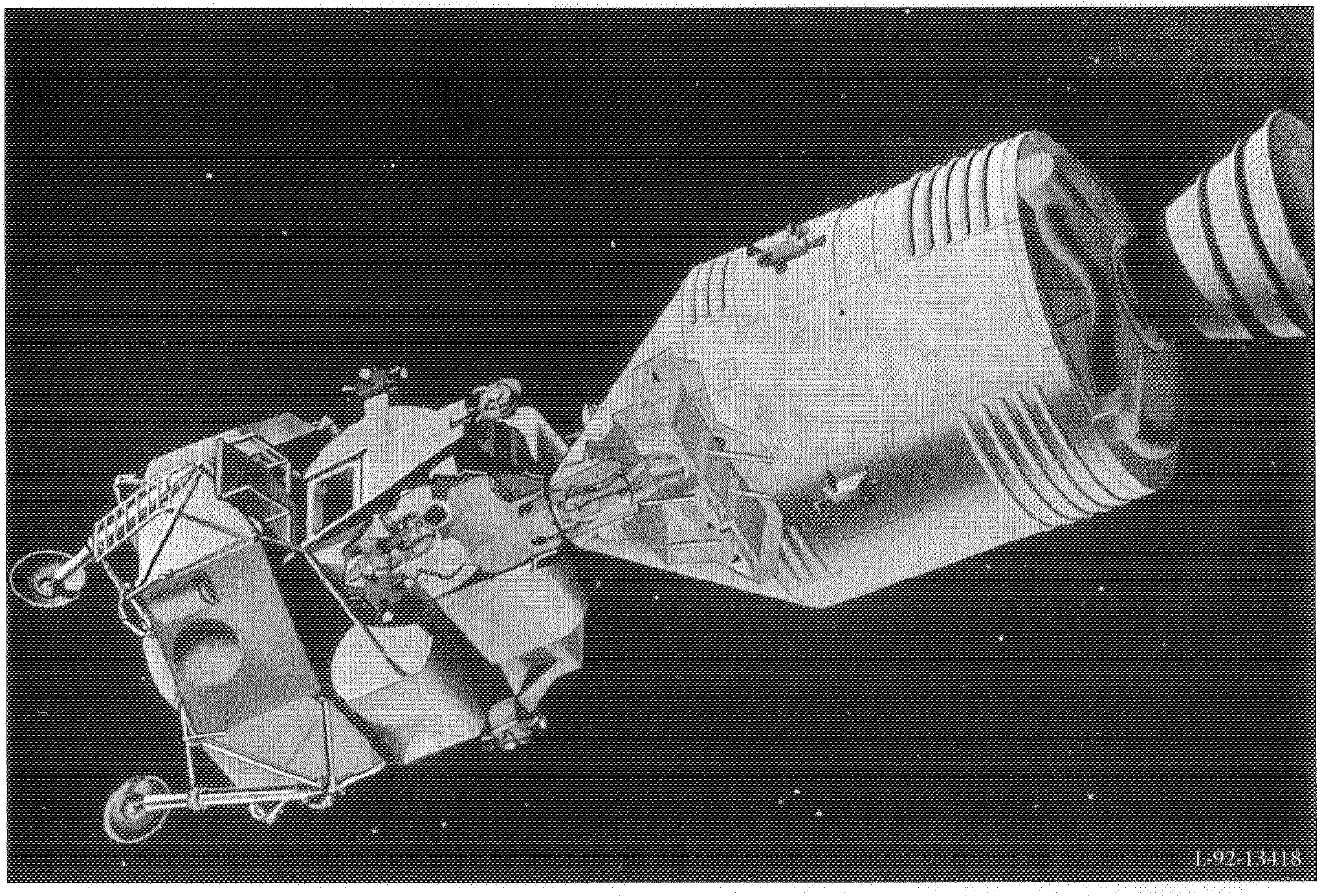
The first of these studies, a very brief paper by William H. Michael, Jr., examined the benefits of "parking" the Earth-return propulsion portion of a spacecraft in orbit around the moon during a landing mission. The main benefit, according to Michael's unpublished 1959 paper, was the weight advantage of a small lunar lander needing less fuel. The chief problems were the "complications involved in requiring a rendezvous with the components left in the parking orbit."

In December 1960, after different LOR mission concepts had been formulated, several Langley researchers, including Ralph W. Stone, Clinton E. Brown, John D. Bird, Max C. Kurbjun, and Houbolt, made formal presentations on their concepts to the incoming associate administrator of NASA, Dr. Robert C. Seamans. Although Seamans seemed sufficiently impressed, the LOR concept was to remain something of an orphan within the NASA family at every place except Langley for some time to come.

Twenty months later, on July 11, 1962, after much technical debate and in-fighting, Seamans and NASA Administrator James E. Webb announced during a press conference at NASA Headquarters in Washington, D.C., that lunar-orbit rendezvous had been selected as the primary mission mode for the initial manned moon landing. Considering the strong opposition to LOR during NASA's intensive evaluation of possible mission modes for Apollo, the choice seemed quite unlikely.



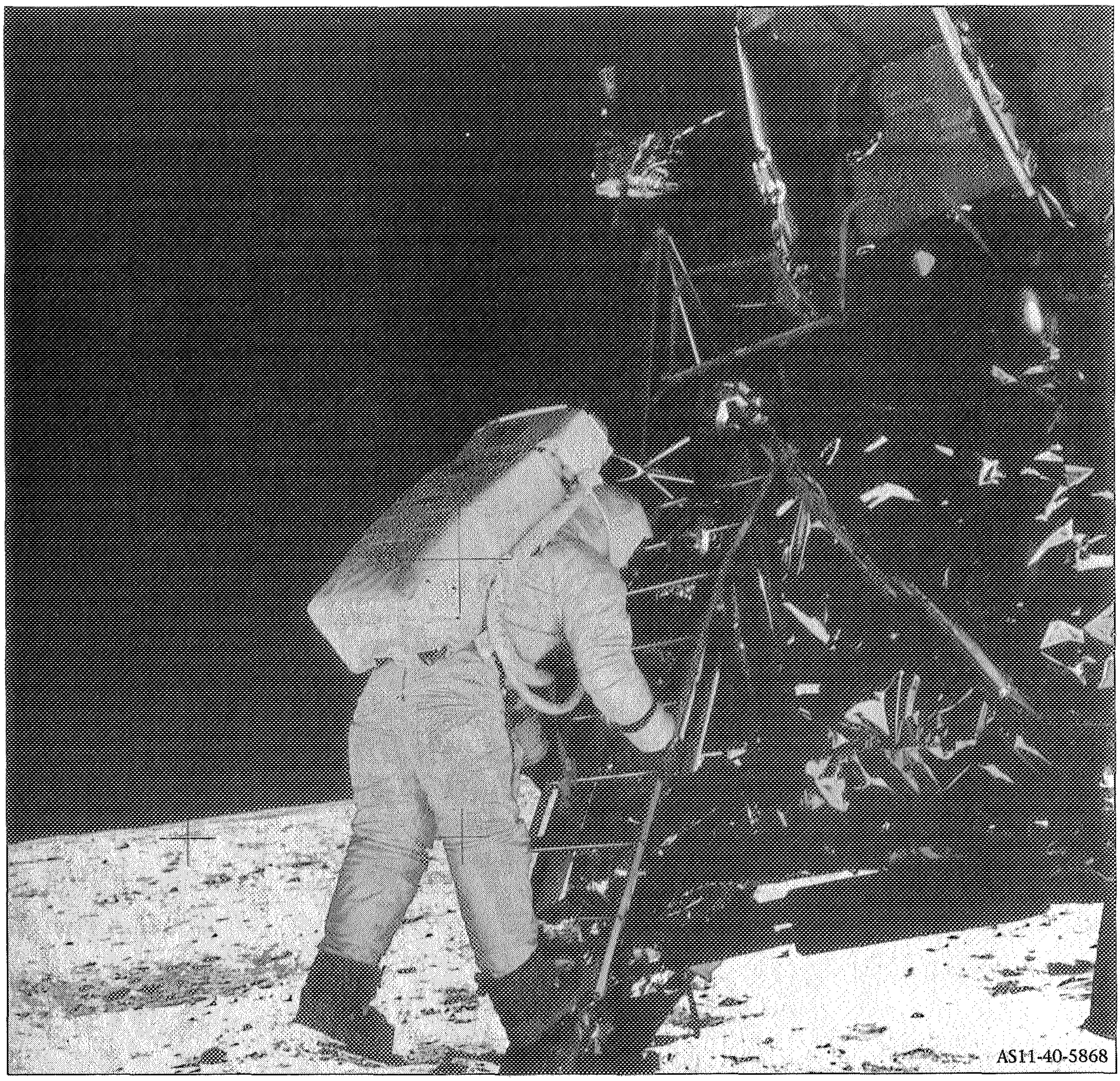
Once in Earth orbit, the last stage of the Saturn rocket fires, boosting the Apollo spacecraft and its three-man crew into its flight trajectory to the moon.



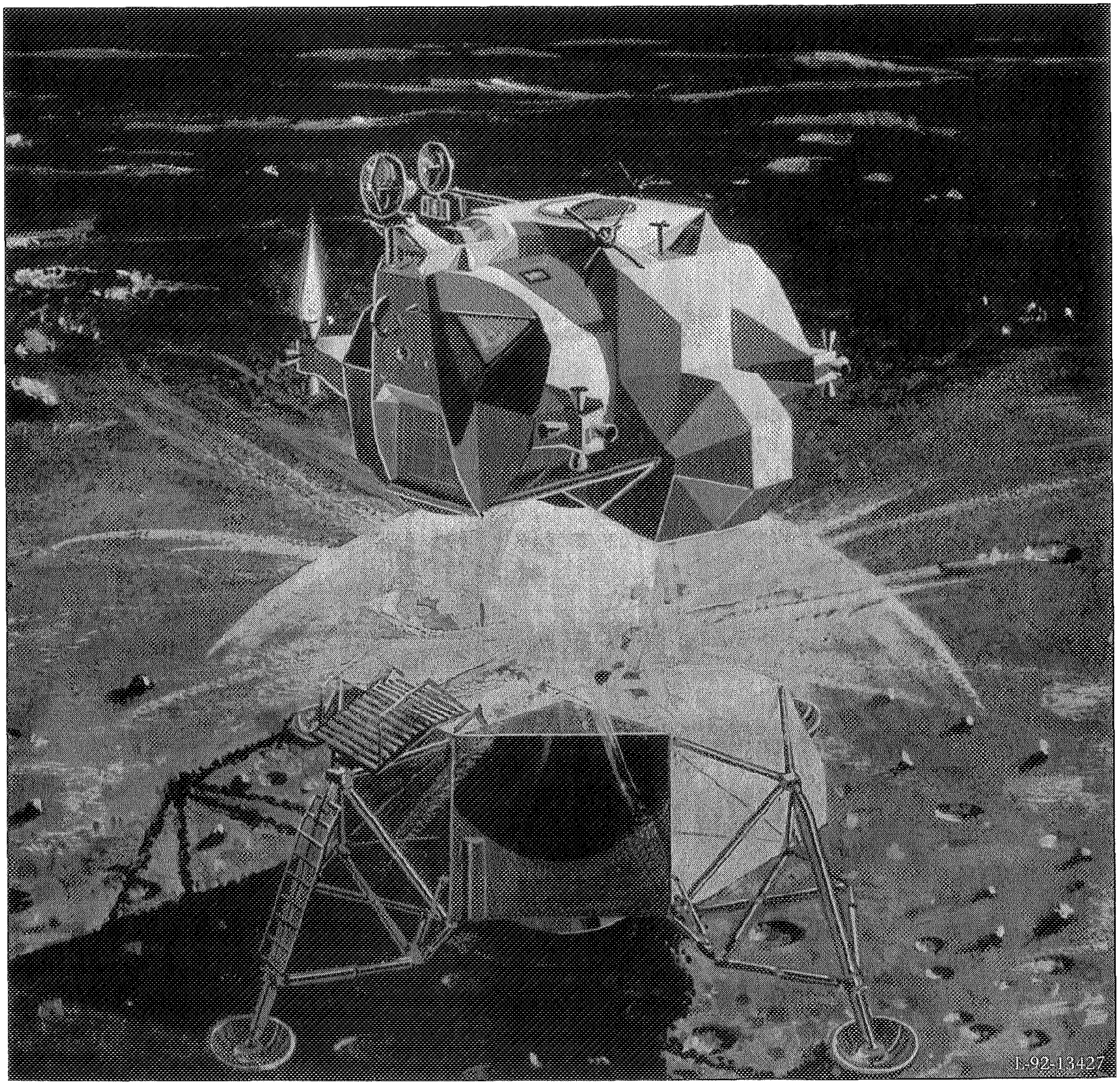
Once in lunar orbit, two of the crew members donned spacesuits and climbed into the lunar excursion module, detached it from the mother ship and "flew" it down to the lunar surface.

When Langley engineers first suggested the concept of lunar-orbit rendezvous, NASA had rejected it out of hand for being too complicated and risky. If rendezvous had to be part of Project Apollo, critics of LOR felt that it should be done only in Earth orbit. If that rendezvous failed, the threatened astronauts could be brought back home simply by allowing the orbit of their spacecraft to deteriorate. But if a rendezvous around the moon failed, the astronauts would be too far away to be saved. Nothing could be done.

In retrospect, we know that LOR enjoyed several advantages over the other two options. It required less fuel, only half the payload, and less brand new technology than the other methods; it did not require the monstrous Nova rocket; and it called for only one launch from Earth whereas EOR required two. Only the small lightweight lunar module, not the entire spacecraft, would have to land on the moon. This was perhaps LOR's major advantage. Because the lander was to be discarded after use and would not need to return to Earth, NASA could tailor the design of the LEM for maneuvering flight



The second man on the moon, Buzz Aldrin descends from the lunar module on July 20, 1969. He and astronaut Neil Armstrong spent two hours and 20 minutes walking on the moon. The small, lightweight Lunar Module was a major advantage of the LOR concept because it did not need to be returned to Earth.

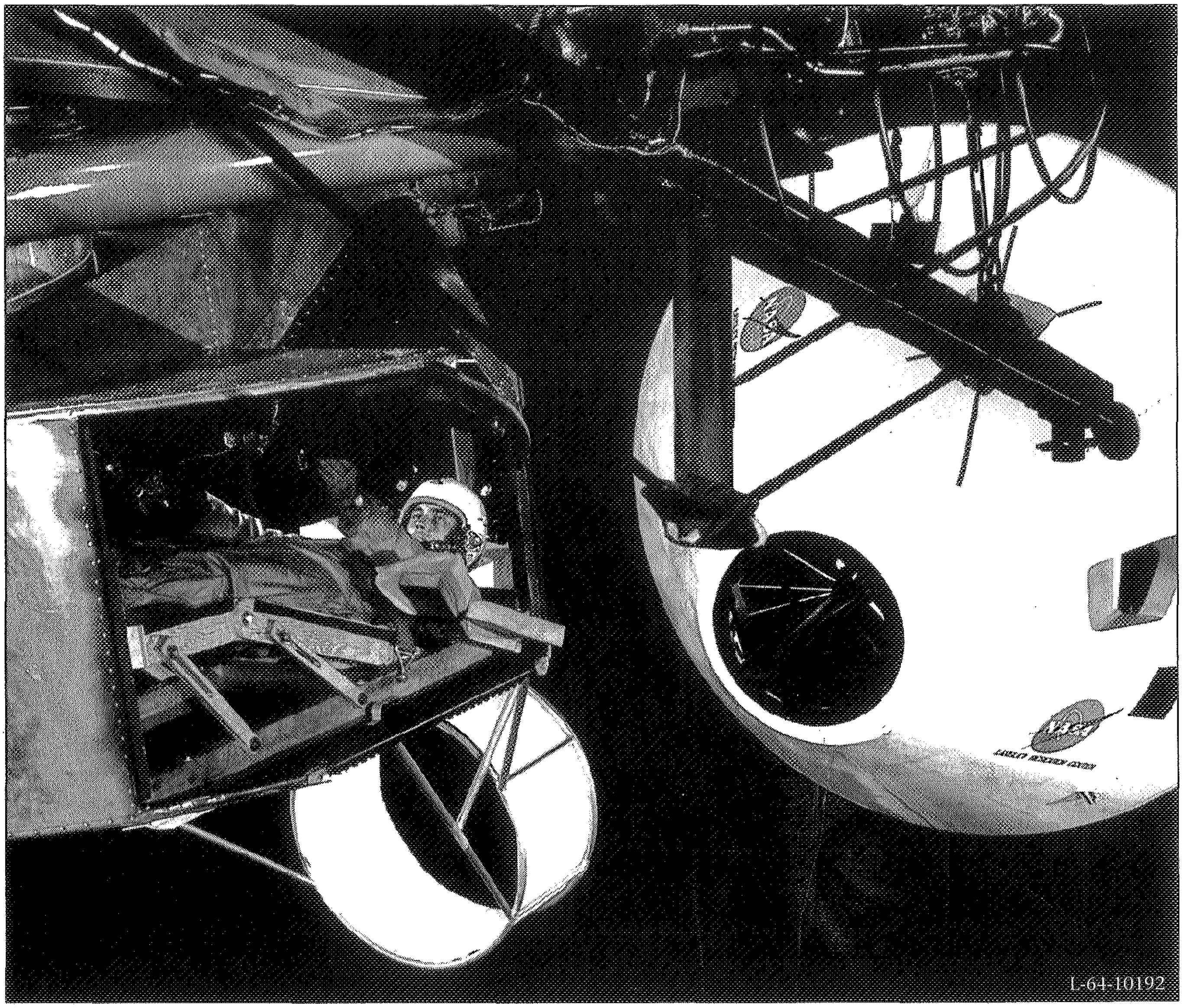


The lunar module ascent stage (upper portion) is shown using its ascent engine to rocket back into lunar orbit and rendezvous with the Command Module (still orbiting the moon). Success depended on Langley's ability to train the astronauts to master the techniques of landing the lunar module on the lunar surface and returning the ascent stage to orbit to dock with the mother ship.

in the lunar environment and for a soft lunar landing. In fact, the beauty of LOR was that it meant that NASA could tailor all of the modules of the Apollo spacecraft independently.

But in 1962 all these advantages were theoretical. On the other hand, the fear that American astronauts might be left in an orbiting coffin was quite real. It was a specter that haunted the dreams of those responsible for the Apollo program and one that made objective evaluation of the lunar-orbit rendezvous concept by NASA unusually difficult.

In late 1961 and early 1962 NASA convened a number of internal task forces to help in the selection of the mission mode for Apollo. One of these committees (the Lundin Committee) evaluated the option of direct ascent; another (the Heaton Committee) investigated the feasibility of Earth-orbit rendezvous; but there was no committee to look into LOR. Only one of these study groups (the Lundin Committee) wanted to hear anything about lunar-orbit rendezvous, and in its final report LOR finished a distant third behind EOR and direct ascent.

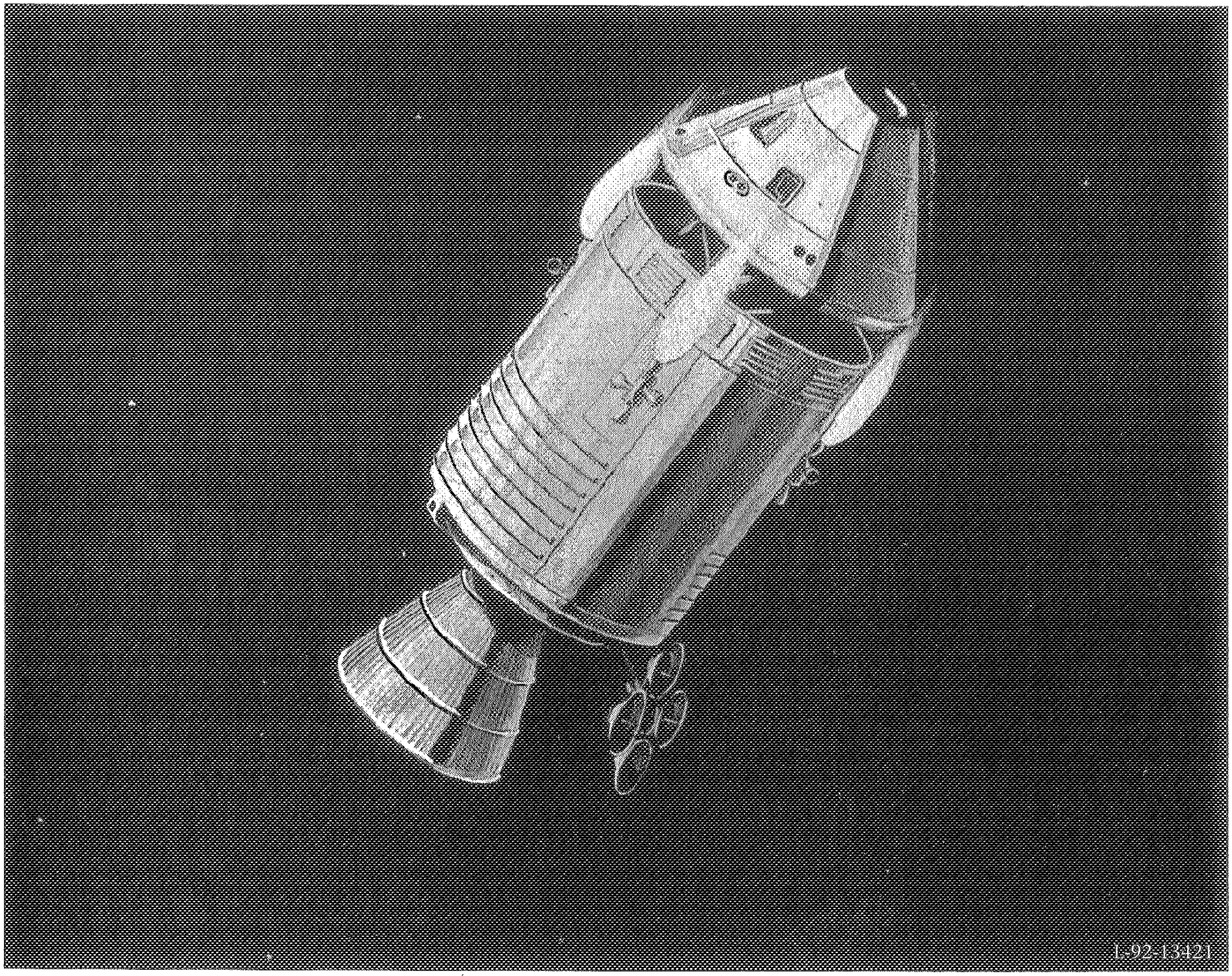


Lunar orbit rendezvous required docking the lunar module with the command module in lunar orbit. Astronauts practiced the complex task of separating and uniting spacecraft to master docking techniques with Langley's Rendezvous and Docking Simulator, today a National Historic Landmark, pictured.

But at least one tenacious Langley engineer, Dr. John Houbolt, would not let the advantages of LOR be ignored. As a member of the Lunar Mission Steering Group, Houbolt had been studying various technical aspects of space rendezvous since 1959 and was convinced, like several others at Langley, that LOR was not only the most feasible way to make it to the moon before the decade was out, it was the only way. He had reported his findings to NASA on various occasions but felt strongly that the internal task forces (to which he made presentations) were following arbitrarily established "ground rules." According to Houbolt, these ground rules were constraining NASA's thinking about the lunar mission—and causing LOR to be ruled out before it was fairly considered.

In November 1961 Houbolt took the bold step of skipping proper channels and writing a private letter, nine pages long, directly to Seamans, the associate administrator. "Somewhat as a voice in the wilderness," Houbolt protested LOR's exclusion. "Do we want to go to the moon or not?" the Langley engineer asked. "Why is Nova, with its ponderous size simply just accepted, and why is a much less grandiose scheme involving rendezvous ostracized or put on the defensive? I fully realize that contacting you in this manner is somewhat unorthodox," Houbolt admitted, "but the issues at stake are crucial enough to us all that an unusual course is warranted."

It took two weeks for Seamans to reply to Houbolt's extraordinary letter. The associate administrator

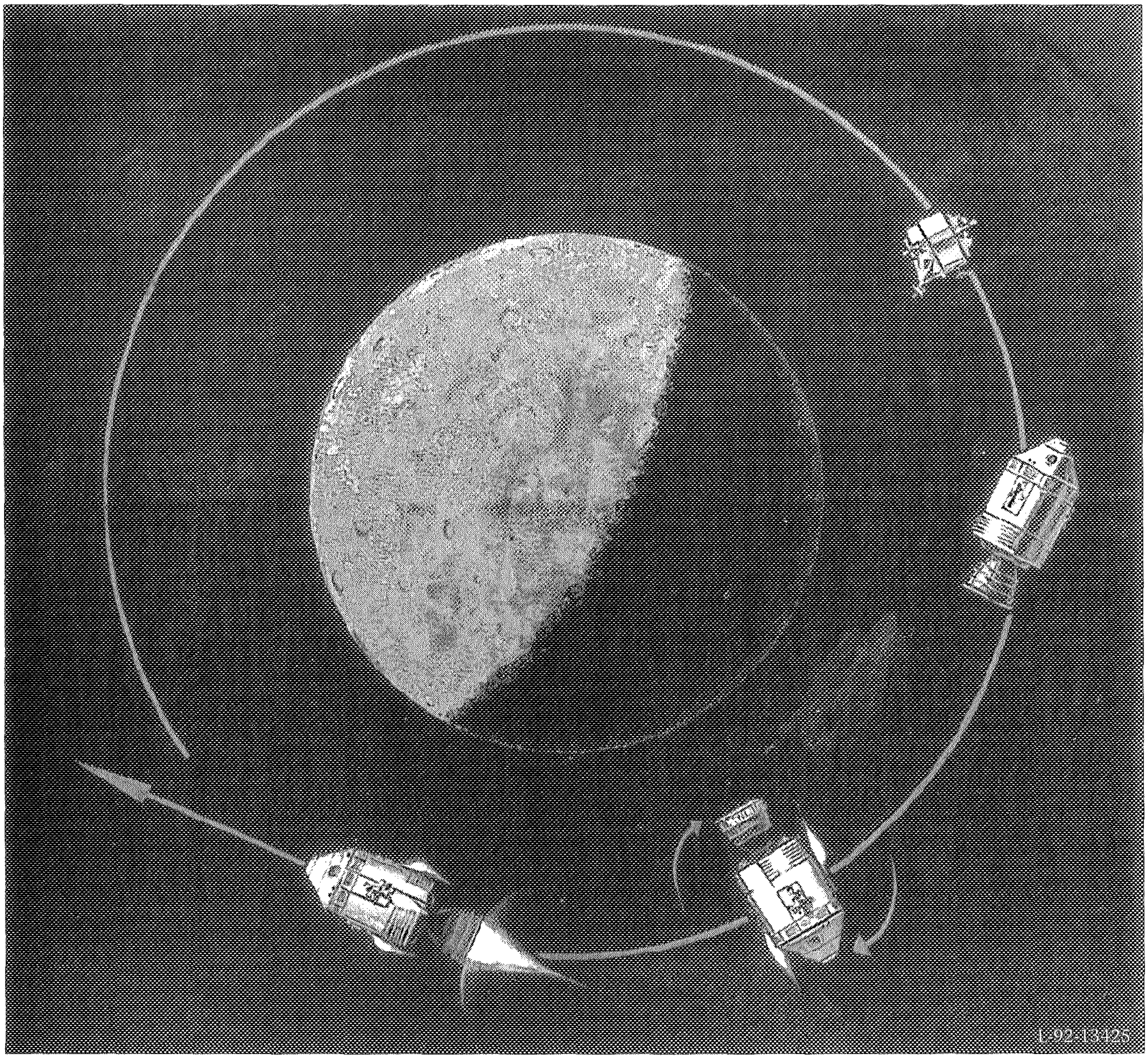


Upon return to Earth, the command and service modules separate, leaving the command module to plunge into the Earth's atmosphere at a velocity of 25,000 mph.

agreed that "it would be extremely harmful to our organization and to the country if our qualified staff were unduly limited by restrictive guidelines." He assured Houbolt that NASA would in the future be paying more attention to LOR than it had up to this time.

In the following months, NASA did just that, and to the surprise of many both inside and outside the agency, the darkhorse candidate, LOR, quickly became the front runner. Several factors decided the issue in its favor. First, there was growing disenchantment with the idea of direct ascent due to the time and money it was going to take to develop the huge Nova rocket. Second, there was increasing technical apprehension over how the relatively large spacecraft demanded even by Earth-orbit rendezvous would be able to maneuver to a soft landing on the moon. As one NASA engineer who changed his mind explained: "The business of eyeballing that thing down to the moon really didn't have a satisfactory answer. The best thing about LOR was that it allowed us to build a separate vehicle for landing."

The first major group to break camp in favor of LOR was Robert Gilruth's Space Task Group, which was still located at Langley but was soon to move to Houston. The second to come over was the Von Braun team in Huntsville. Then these two powerful groups of converts, along with the original true believers at Langley, persuaded key officials at NASA Headquarters, notably Administrator James Webb, who had been holding out for direct ascent, that LOR was the only way to land on the moon by 1969. With the key players inside NASA lined up behind the concept, Webb approved LOR in July 1962. He did it even though President Kennedy's science adviser, Jerome Wiesner, remained firmly opposed to LOR.



Sequences of lunar de-orbit to Earth, which Michael Collins called "the get us out of here, we don't want to be a permanent moon satellite" maneuver.

Whether NASA's choice of LOR would have been made in the summer of 1962 or at any later time without the research information, the commitment, and the crusading zeal of Houbolt and his associates at NASA Langley is a matter for historical conjecture. However, the basic contribution made by the Langley researchers is beyond debate. They were the first in NASA to recognize the fundamental advantages of the LOR concept, and for a critical period of time in the early 1960s they were also the only ones inside of the agency to foster it and fight for it.

Thousands of factors contributed to the ultimate success of Apollo, but no single factor was more essential than the concept of lunar-orbit rendezvous. Without NASA's adoption of this stubbornly-held minority opinion, we may still have gotten to the moon, but almost certainly it would not have been accomplished by the end of the decade, as President Kennedy had wanted.

But one can take this "what-if" scenario even farther. Without LOR, it is very possible that we still would not have not landed on the moon. No other way but LOR could solve the landing problems.

This NASA Facts was prepared by the NASA Langley Research Center Office of Public Affairs with the assistance of Dr. James R. Hansen, author of ***Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958.***

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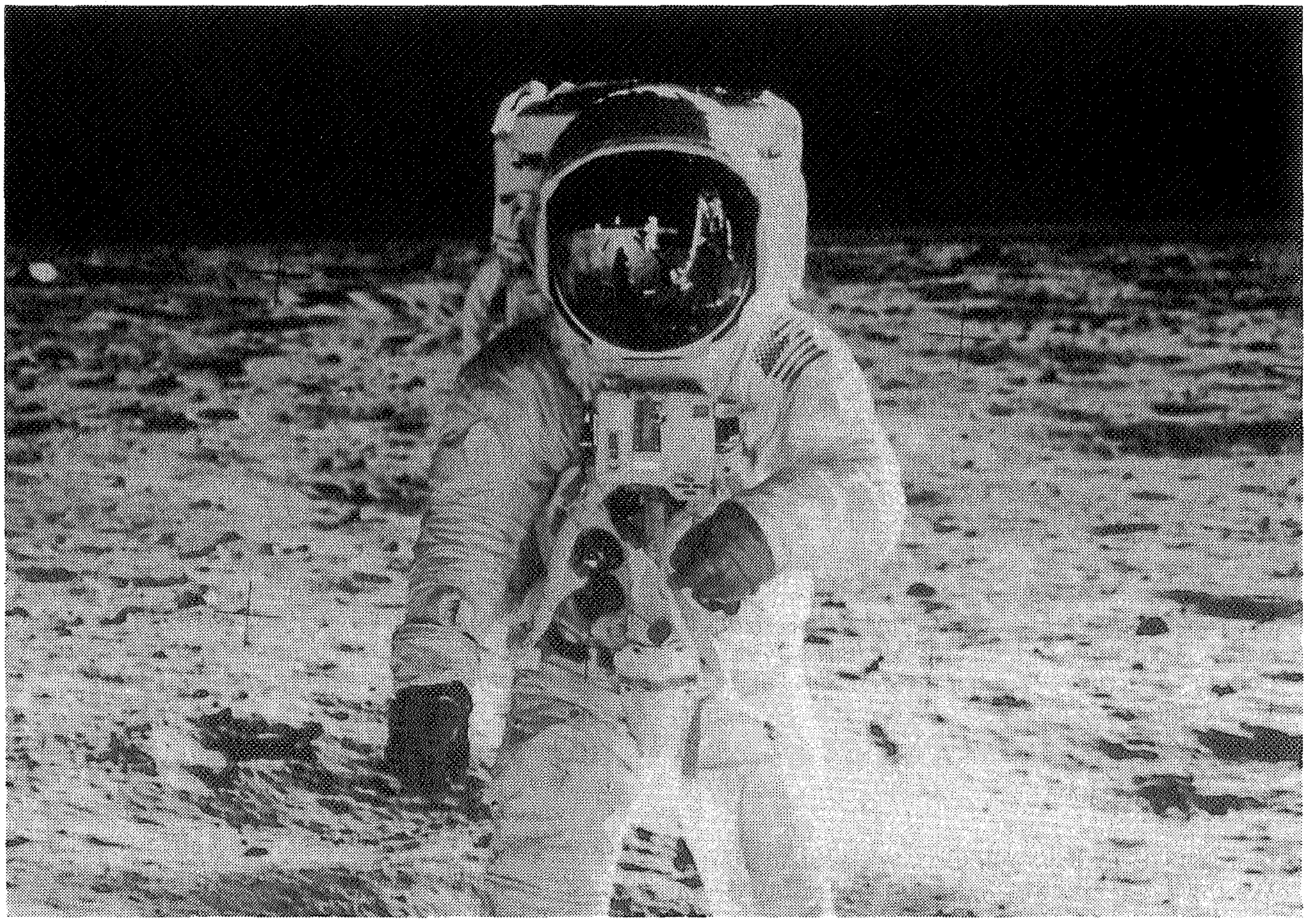
NASA Langley Research Center's Contributions to the Apollo Program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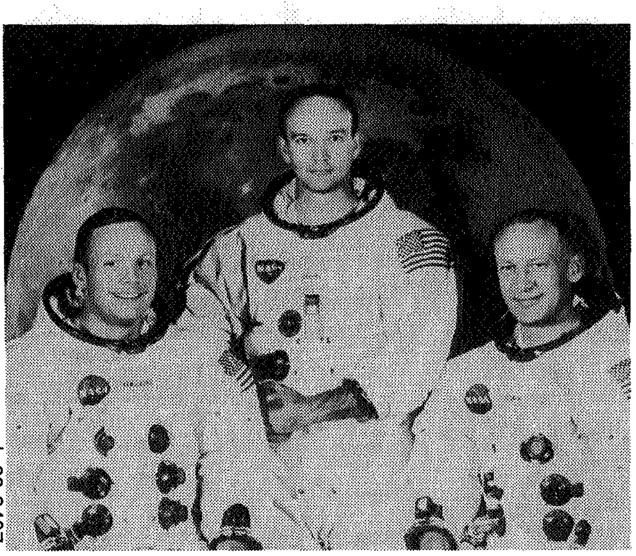
Astronaut Buzz Aldrin, Lunar Module pilot, photographed on the lunar surface by Astronaut Neil A. Armstrong, commander of the Apollo 11 mission, 1969.

More than twenty years after the first manned landing on the moon, President Kennedy's commitment to the lunar mission sounds as bold as it ever did: American astronauts should fly a quarter of a million miles, make a pinpoint landing on a strange planet, blast off it and return home safely after an eight-day voyage through space. When Kennedy challenged the nation to risk this incredible journey, the only United States manned spaceflight up to that time had been Alan B. Shepard's 15-minute suborbital excursion in Mercury capsule, Freedom 7. NASA was not exactly sure how the lunar mission should be made at all, let alone achieved in less than ten years' time.

Answering President Kennedy's challenge and landing men on the moon by 1969 required the most sudden burst of technological creativity, and the largest commitment of resources ($24 billion), ever made by any nation in peacetime. At its peak, the Apollo program employed 400,000 Americans and required the support of over 20,000 industrial firms and universities.

This NASA Facts pays tribute to the contributions NASA's Langley Research Center made to the first manned lunar landing, made July 20, 1969, by Apollo 11 astronauts Neil A. Armstrong, commander; Michael Collins, Command Module pilot; and Edwin E. "Buzz" Aldrin, Lunar Module pilot.



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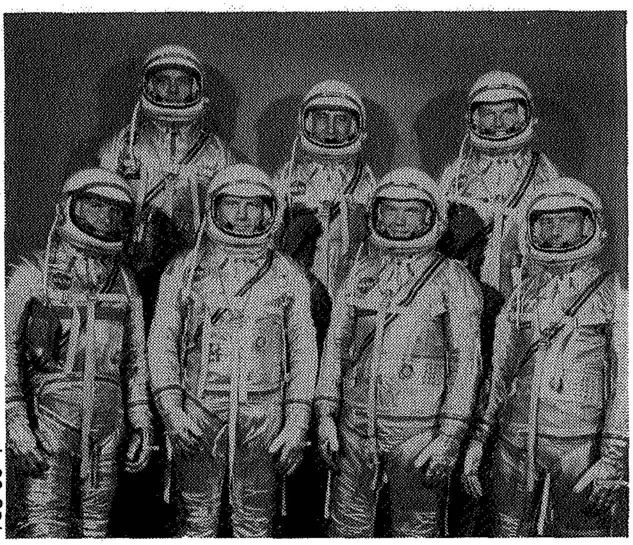
The crew of Apollo 11 included, from left to right, Neil A. Armstrong, commander; Michael Collins, Command Module pilot; and Buzz Aldrin, Lunar Module pilot.

Background

The Langley Research Center, established in 1917, was the first U.S. national laboratory devoted to the advancement of the science of flight. Long before the space program, scientists and engineers at Langley incubated the ideas and hatched the technology that made American aviation take off and fly. For 75 years now, information from the laboratory's wind tunnels and other unique research facilities has played a vital role in advancing American performance in the air.

Langley gave birth to key components of the U.S. space program. As early as 1952, Langley researchers explored seriously the possibilities of manned flight into space. Out of these pioneering studies grew the NASA Space Task Group that conceived and directed Project Mercury, America's original man-in-space program. Langley provided much of the knowledge and know-how basic to the development of the Mercury spacecraft and its related systems, as well as to the creation of the worldwide tracking network that monitored the first space shots. Furthermore, it was at Langley where the original team of NASA astronauts (Alan Shepard, Virgil "Gus" Grissom, John Glenn, Scott Carpenter, Donald "Deke" Slayton, Walter Schirra and Gordon Cooper) received their basic training.



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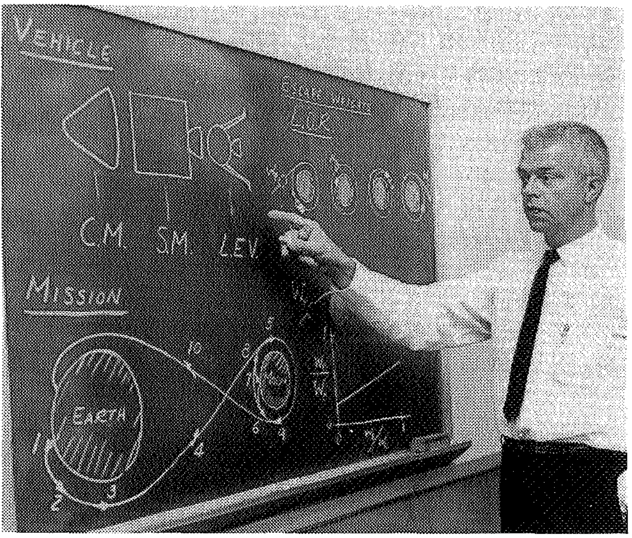
NASA's seven original astronauts, who trained at Langley for Project Mercury were, from left to right, (top) Alan Shepard, Virgil "Gus" Grissom, Gordon Cooper, (bottom) Walter Schirra, Donald Slayton, John Glenn, and Scott Carpenter.

How to get to the moon?

When President Kennedy made his historic decision in May 1961, NASA had already studied various ways by which to land men on the moon but the agency was still uncertain which one was best. Mission planners quickly narrowed the options down to three: direct ascent, Earth-orbit rendezvous (EOR) and lunar-orbit rendezvous (LOR).

Of the three, LOR was initially the least popular inside of NASA due to what was then considered its greater complexity and risks.



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John C. Houbolt explains the Lunar Orbit Rendezvous (LOR) concept. Without this successful mission concept, the United States may have still landed men on the moon, but it probably would not have happened by the end of the 1960s as directed by Kennedy. The basic premise of LOR was to fire an assembly of three spacecraft into Earth orbit on top of a single powerful rocket.

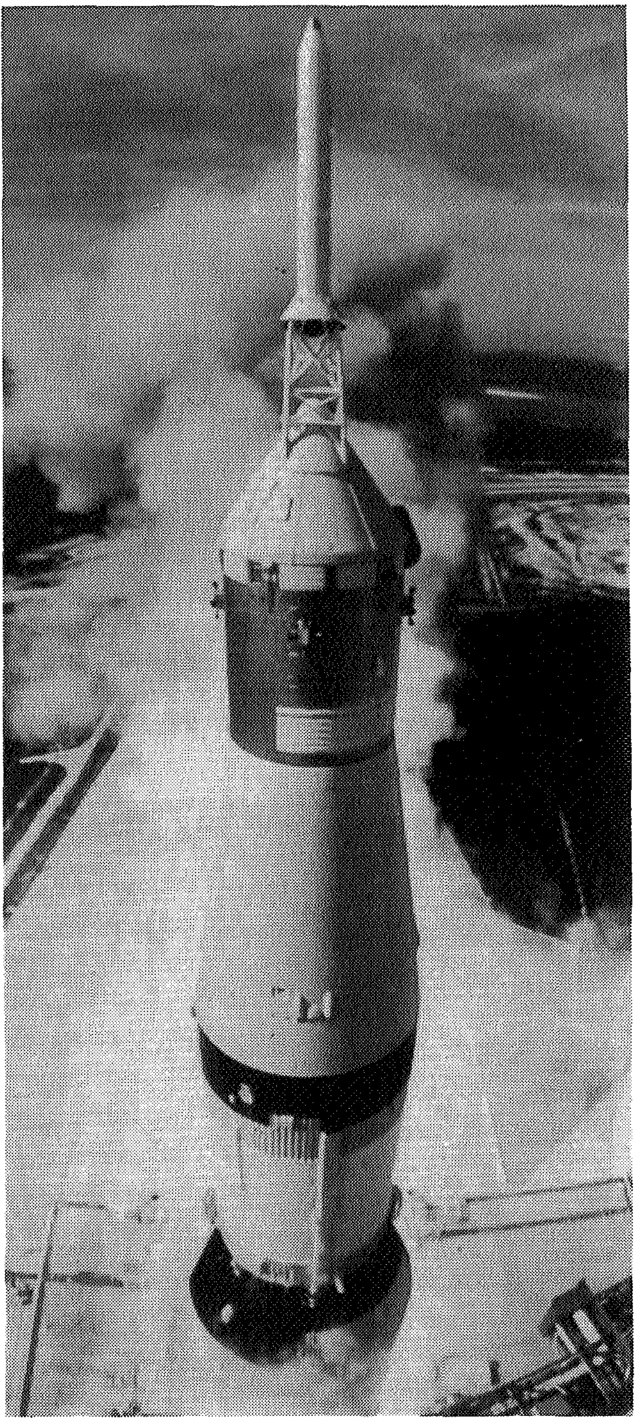
In July 1962, however, after months of evaluation and intense debate, NASA selected LOR as the primary mission mode by which to land Americans on the moon "before the decade is out."

Direct ascent, the first choice of many NASA officials, was ruled out because the huge new launch vehicle required to accomplish the mission—the proposed Nova rocket—would take too much time to develop. The EOR concept was ruled out because it required two separate launch vehicles.

NASA selected LOR only after Langley researchers proved the feasibility of rendezvous in space and revealed the important engineering and economic advantages of a manned moon landing through lunar-orbit rendezvous. Advocates of LOR at Langley played vital roles in convincing NASA leadership that LOR was not only as safe as either direct ascent and Earth-orbit rendezvous but also it promised mission success some months earlier.

Lunar-Orbit Rendezvous (LOR) Concept

The brainchild of a few true believers at NASA Langley who had been experimenting with the idea since 1959, the basic premise of LOR was to fire an assembly of three spacecraft into Earth orbit on top of a single powerful rocket (Saturn V).



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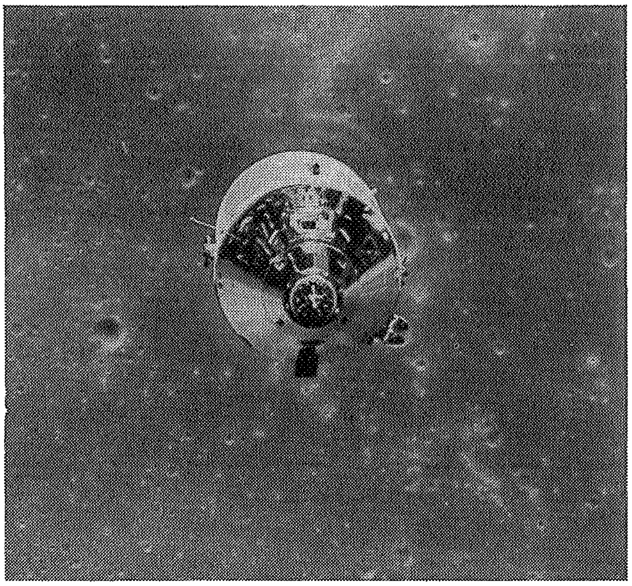
Apollo 11 rises past the launch tower at Pad 39A to begin man's first lunar landing mission. Liftoff occurred at 9:32 a.m., July 16, 1969. The launch vehicle was a Saturn V, developed for the Apollo lunar missions. With the Apollo spacecraft, the Saturn V stood 363 feet tall. Space Shuttle missions are still launched from venerable Pad 39A.

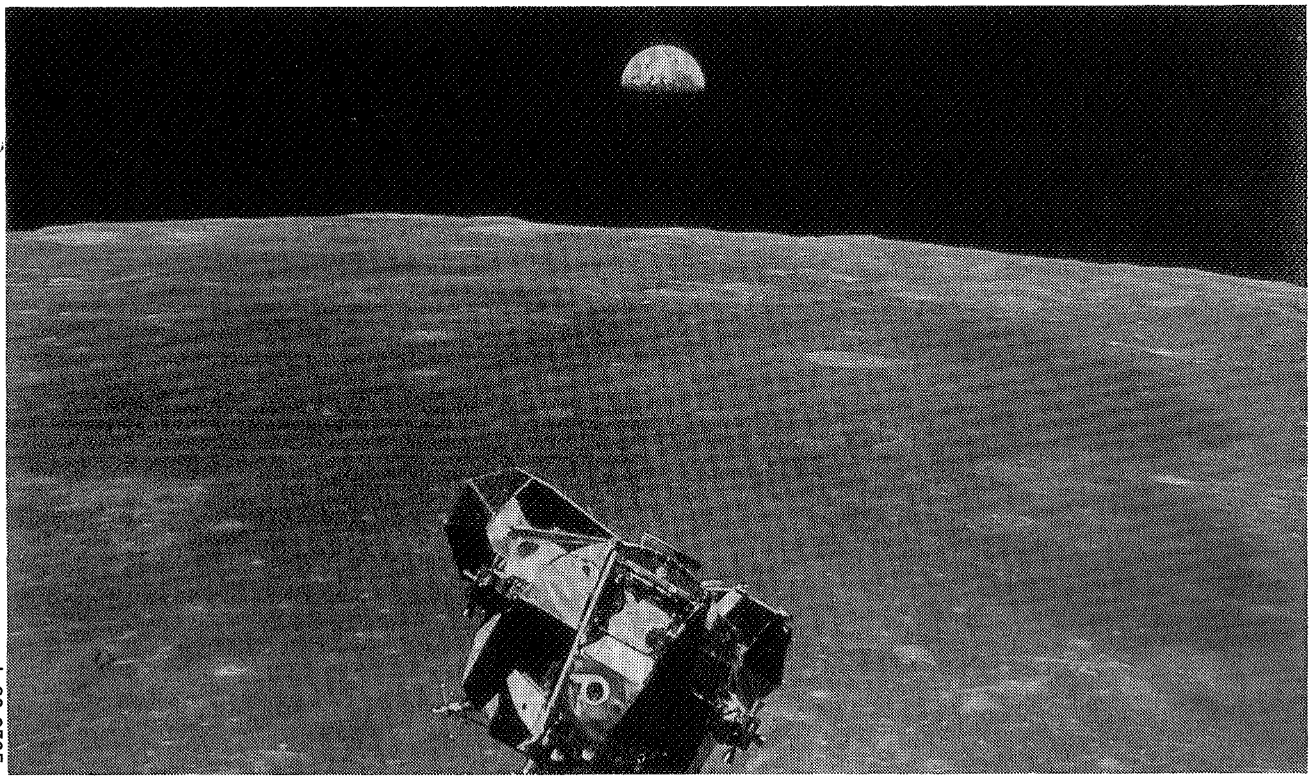
This assembly would include: one, a mother ship or command module (CM); two, a service module (SM) containing the fuel cells, attitude control system and main engine; and, three, a small lunar lander or excursion module. Once in Earth orbit, the last stage of the rocket would fire, boosting the combined Apollo spacecraft into its flight trajectory to the moon. In lunar orbit, two crew members would don space suits and climb into the lunar excursion module (LEM) and take it down to the surface. The third crew member would maintain a lonely vigil in lunar orbit inside the mother ship. After exploring, the LEM would rocket back up and re-dock with the CM. The lander would then be discarded to the vastness of space or crashed into the moon, and the three astronauts in their command ship would head for home.



The Apollo 11 Command and Service Modules are shown here in a photo taken from the Lunar Module in orbit during the Apollo 11 mission. The lunar terrain below is the northeastern portion of the Sea of Fertility.

Langley's bold plan for rendezvous in lunar orbit held out the promise of achieving a manned landing on the moon by 1969, but it presented many technical difficulties. Success depended on NASA's ability to train astronauts to master the techniques of landing the LEM on the lunar surface and returning it to orbit and docking with the mother ship.

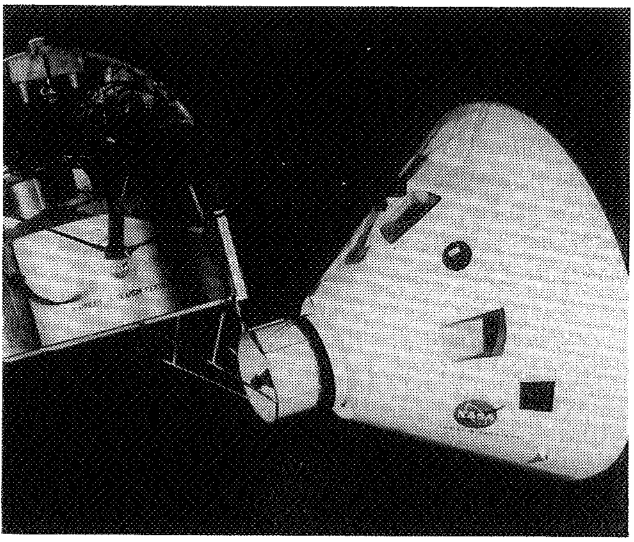
Several of the most significant facilities used to develop techniques for LOR and prepare the astronauts for Apollo missions were designed, built and operated by the Langley Research Center.



Pictured is the Apollo 11 Lunar Module (LM) ascent stage photographed from the Command Module during rendezvous in lunar orbit as the LM was making its docking approach to the Command Module. The large dark colored area in the background is Smith's Sea. This view is looking west. The Earth rises above the lunar horizon.

Rendezvous Docking Simulator

One of the trickiest yet most essential maneuvers that had to be perfected on the ground before it could be tried in space was the linking of the Lunar Excursion Module and the Command Module. The ability to rendezvous and dock the two vehicles in space was critical to the success of LOR, because if there were a failure the two astronauts in the LEM would have no means to return to Earth—and NASA would have no means to rescue them. The first men on the moon, international heroes, would die inside the LEM, and the commander of the CM would be forced to leave his buddies in their orbiting coffin and head for home alone. Nothing was secretly more terrifying to the CM commander than this possibility.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Langley's Rendezvous and Docking Simulator was used by NASA scientists to study the complex task of docking the Lunar Module with the Command Module in lunar orbit.

NASA had to do everything it could to make sure that this tragedy did not happen.

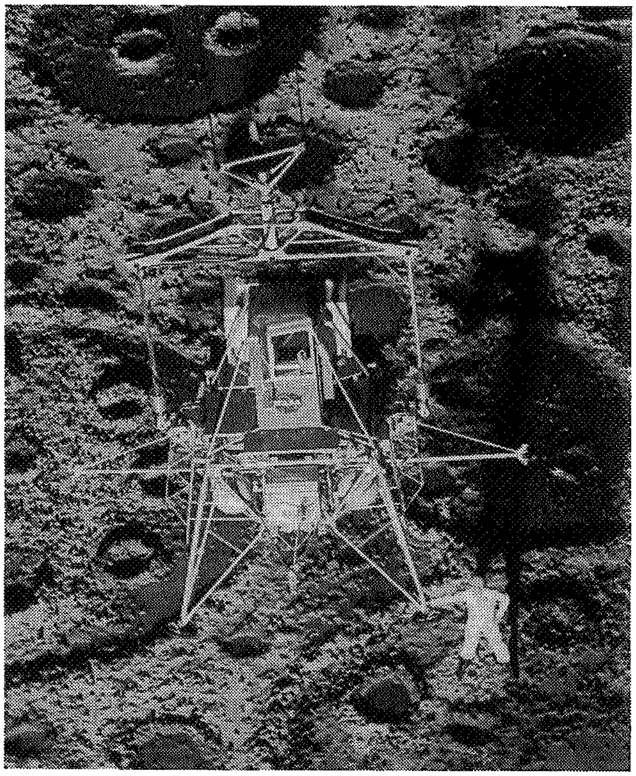
In the early 1960s, Langley researchers built various simulators to study the feasibility of space rendezvous and orbital docking. The most advanced of these, the Rendezvous Docking Simulator, significantly improved the chances of mission success through LOR by giving the astronauts a routine opportunity to pilot dynamically-controlled scale-model vehicles in a safe and controlled three-dimensional environment closely approximating that of space.

Rendezvous in space could turn sour with paralyzing swiftness. An on-board computer might fail, a gyroscope might tilt the wrong way, or some other glitch might occur to complicate the performance of a necessary maneuver. Pilots of both the LEM and the CM had to be ready to make crucial decisions instantaneously. Without Langley's Rendezvous Docking Simulator, the astronauts would not have been nearly as well prepared for handling the pressures of LOR. With the help of this ingenious device, they were able to master all of the necessary rendezvous and docking skills before liftoff.

Lunar Landing Research Facility

Before confronting the serious challenges of rendezvous and docking, the goal of the Apollo astronauts was first to achieve a successful lunar landing. To help solve this part of the overall problem of an LOR mission, Langley engineers constructed the Lunar Landing Research Facility.

NASA needed such a facility in order to explore and develop techniques for landing the rocket-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The Lunar Excursion Module Simulator here at Langley's Lunar Landing Research Facility enabled astronauts to practice landing on the lunar surface. This training gave Neil Armstrong, Alan Shepard and other Apollo astronauts the opportunity to study and safely overcome problems that could have occurred during the final 150-foot descent to the surface of the moon.

powered LEM on the moon's surface, where the gravity is only one-sixth as strong as on Earth, as well as to determine the limits of human piloting capabilities in the unknown flight medium.

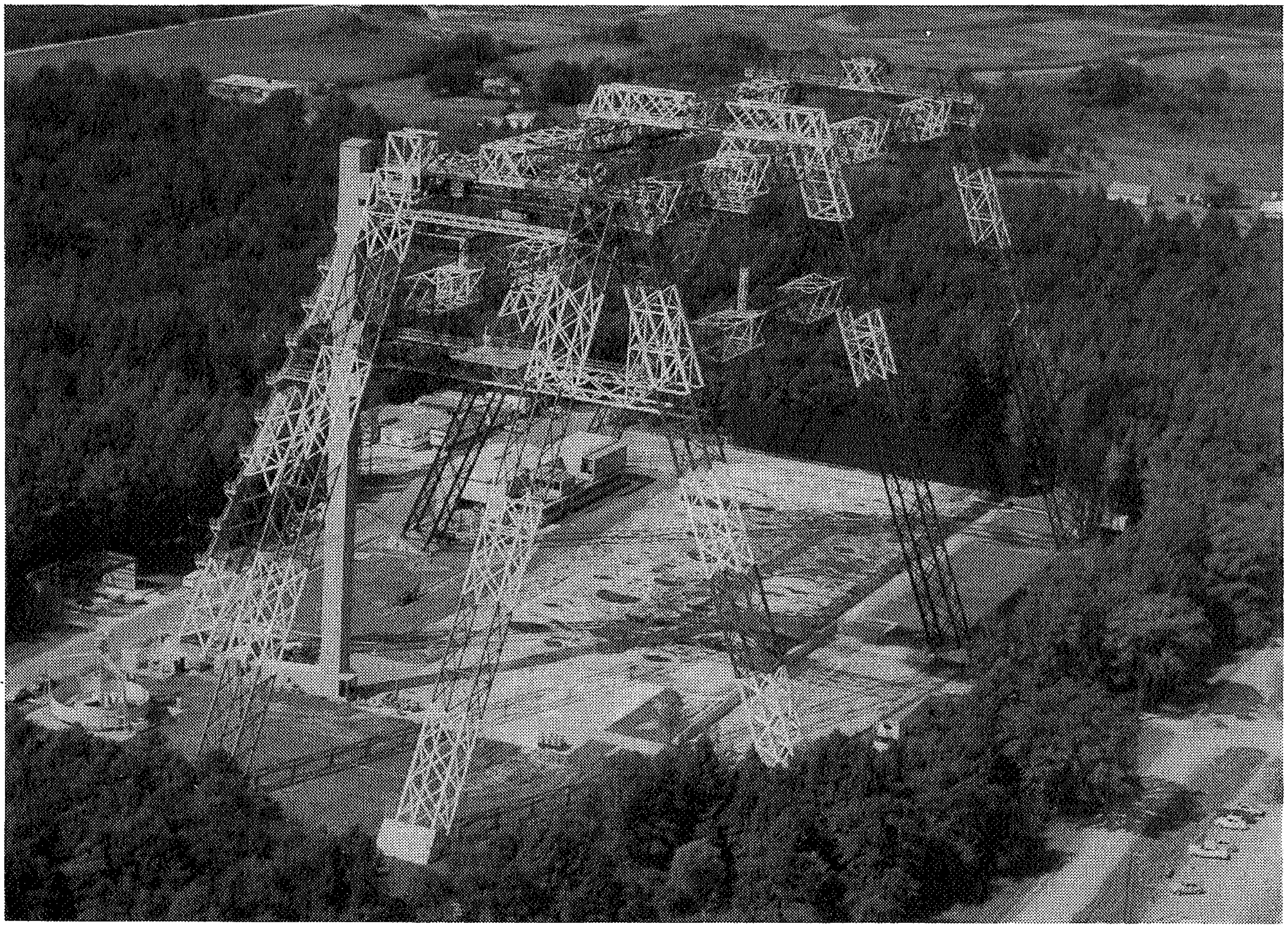
Although NASA Langley did use helicopters in the early 1960s to ascertain some of the problems of vertical descent to a lunar landing, there were no direct parallels between flying an aircraft in the Earth's atmosphere and piloting the LEM in the vacuum of space. If there had been parallels, the LEM would have looked something like a conventional aircraft—which it absolutely did not.

Langley researchers, because they were the early champions of LOR inside of NASA, played the leading role in the original conceptualization of the Lunar Excursion Module, and they knew that the pilot of this vehicle, however its final design turned out, would have to overcome some distinctly unusual problems.

In technical terms, control of the LEM required small rockets that operated in an on-off manner. The firing of these control rockets in space produced abrupt changes in torques—forces that tended to produce rotation or rolling—rather than the smoothly modulated torques of a helicopter.

Furthermore, the LEM would hover in space with only one-sixth of the thrust required for a vehicle of the same weight in Earth's gravity. This meant that the characteristics of the LEM's control system would be significantly different from those of any flight vehicle to which the astronauts were accustomed. They could not simply extrapolate from atmospheric flight to flight in lunar conditions. In key respects, in fact, some of their basic previous experience in flying machines might even confuse them and get in their way.

Langley's Lunar Landing Research Facility, completed in 1965, helped to prepare the Apollo astronauts for the final 150 feet of their lunar landing mission by simulating both the lunar gravity environment and full-scale LEM vehicle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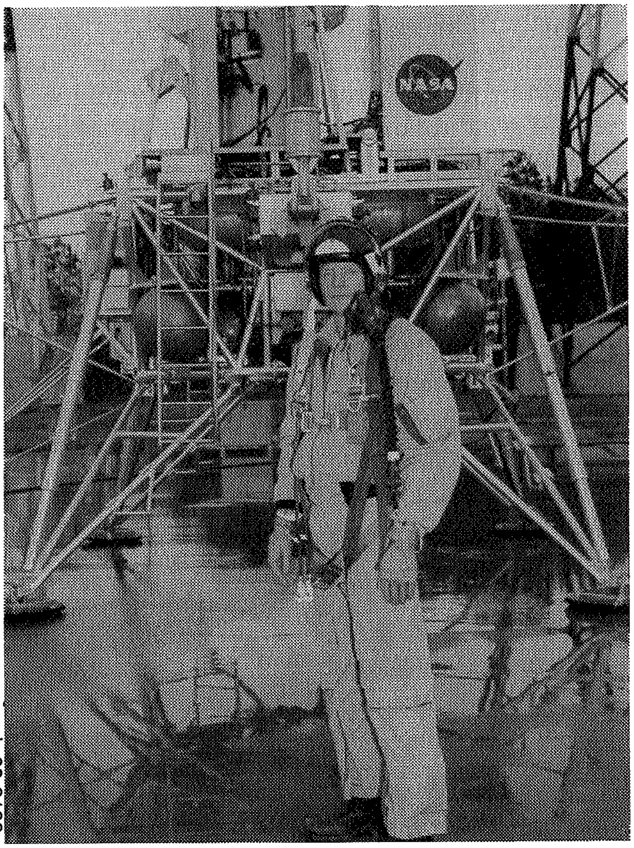
Apollo astronauts perfected their piloting and moon walking techniques at Langley's 250-foot high Lunar Landing Research Facility, here with a simulated lunar surface. The site was named a National Historic Landmark for its contributions to manned spaceflight programs.



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Before Neil Armstrong first touched down on the moon in 1969, he and other astronauts had plenty of practice at Langley on the simulated lunar surface at the Lunar Landing Research Facility. Armstrong became the first human to walk on the moon.

dynamics. The builders of this unique facility effectively cancelled all but one-sixth of Earth's gravitational force by using an overhead partial-suspension system that provided a lifting force by means of cables acting through the LEM's center of gravity.

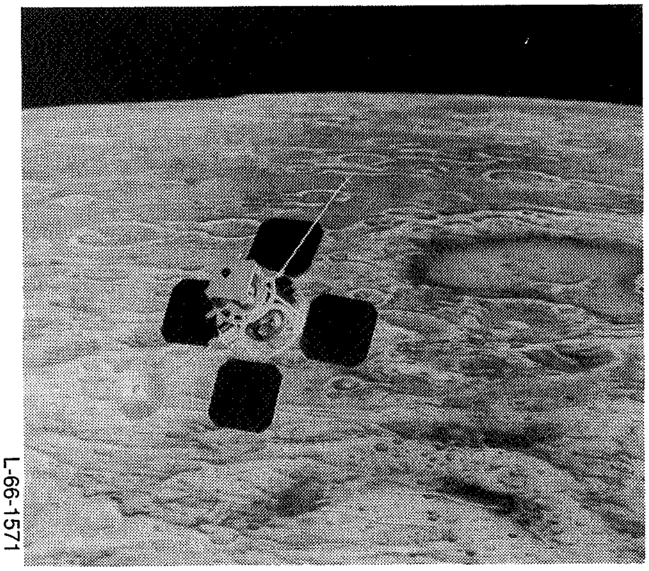
Twenty-four astronauts practiced lunar landings at this facility, the base of which was modeled with fill dirt to resemble the surface of the moon. Neil Armstrong and Buzz Aldrin trained on it for many hours before liftoff of Apollo 11. As was the case with all space missions, the successful landings of the first two men on the moon depended heavily on expert training in ground equipment like Langley's Rendezvous Docking Simulator and Lunar Landing Research Facility.

Langley provided critical information about the lunar landing in other ways as well. A hydraulic analog simulator built at the laboratory in the early 1960s helped researchers determine the ability of a pilot to control vertical braking maneuvers for landings starting from an altitude of about 25 miles above the lunar surface. There was also a special facility using one-sixth scale models of the LEM that looked into the possibility of an impact that could damage or upset the fragile-looking vehicle upon landing. Another laboratory apparatus probed the anticipated and much feared problem that blowing lunar dust caused by the blast of rocket engines might temporarily blind the pilot of the LEM during descent and prevent him from finding a safe spot for landing.

Lunar Orbiter Project

Through its management of the Lunar Orbiter Project, which involved systematic photography of the moon's surface by an unmanned spacecraft in lunar orbit, Langley also played a significant role in the selection of the sites of the Apollo manned landings.

Before NASA could give the go-ahead for a landing attempt, many details had to be learned about the nature of the destination. Although humankind had moved some distance from the fantasy that it was made of green cheese, there still existed all kinds of wild theories about the



L-66-1571

The surface of the moon's equatorial region was photographically mapped during the Lunar Orbiter missions. The maps, compiled at Langley Research Center, provided the detailed topographical information needed to pinpoint the best landing sites, including the exact spot in the Sea of Tranquility chosen for Apollo 11.

moon. One theory said that its surface was covered by a fine layer of dust perhaps 50 feet thick; any type of vehicle attempting to land on it would sink and be buried as in quicksand.

Earth-bound telescopes could not resolve lunar objects smaller than a football stadium, so Apollo mission planners could hardly rely on them for a detailed picture of the lunar surface. To get this information, and separate fact from fancy, NASA in the mid-1960s sent a series of unmanned missions to the moon.

The first of these, Project Ranger, involved the hard landing of small probes equipped with a high-speed camera. Before crashing to their destruction into the moon's surface, the Ranger spacecraft showed that a lunar landing was possible—but definitely not just anywhere. The craters and big boulders had to be avoided.

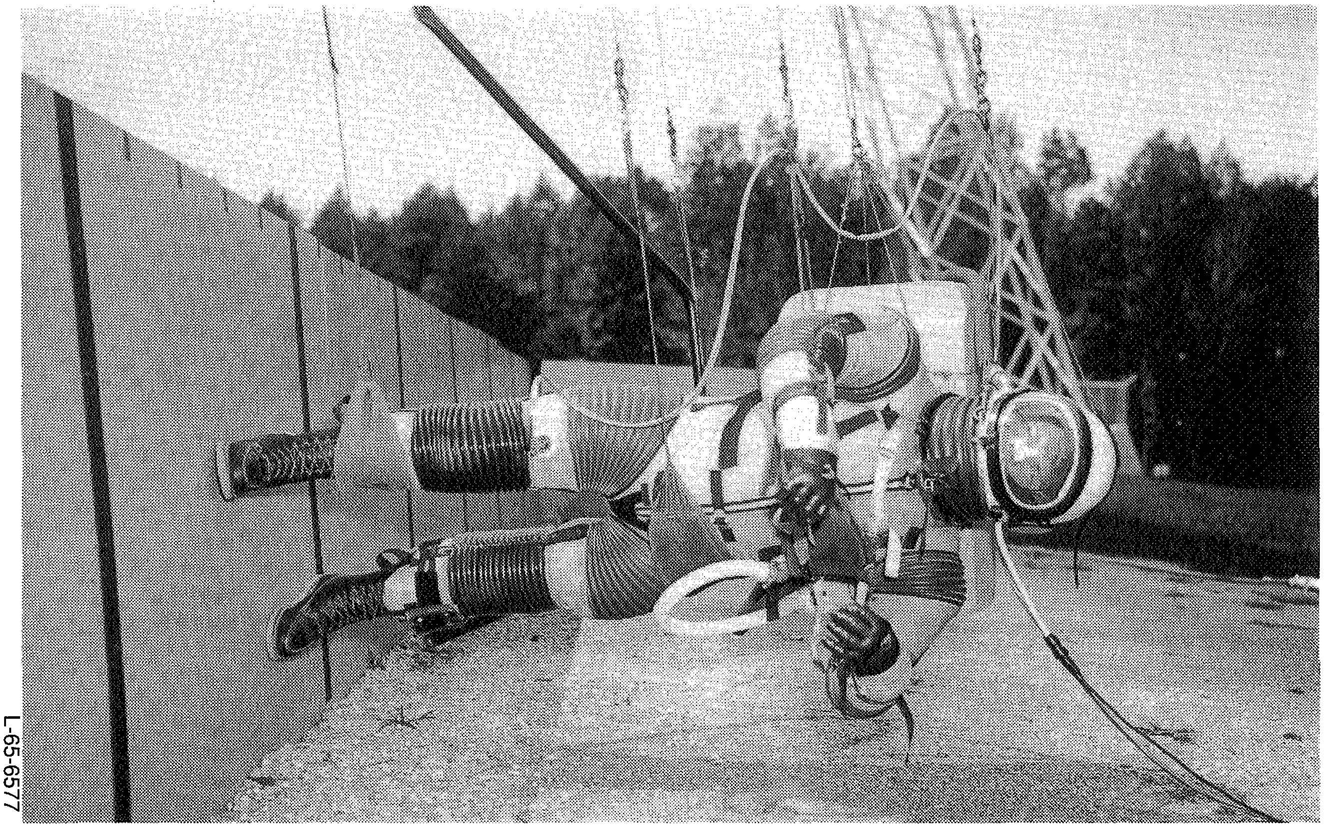
The second probe, Project Surveyor, through its soft landings and photographic data, showed that the lunar surface could easily support the weight and the impact of a small lander.

The third, the Lunar Orbiter Project, made photographic maps of the moon's equatorial regions. These maps, compiled at Langley, provided NASA with the detailed topographical information needed to pinpoint the best landing sites—including the exact spot in the Sea of Tranquility chosen for Apollo 11.

Extravehicular activity

Along with comprehensive studies of astronaut capabilities and mobility in space both inside a spacecraft and during "spacewalks," researchers at Langley also contributed significantly to NASA's understanding of what the Apollo astronauts would and would not be able to do while moving around on the lunar surface.

In the Reduced Gravity Simulator, researchers investigated an astronaut's ability to walk, run and perform the other tasks required in lunar exploration activities. With this facility, NASA studied the effects of one-sixth gravity on self-locomotion by suspending the subject on his side so that he was free to walk on a plane inclined to about 80.5 degrees relative to the local horizons. Holding up the lunar walker so he would not fall



Researchers at Langley Research Center studied astronauts' ability to walk, jump and run using this ingenious lunar-gravity simulator. The astronauts wore pressure suits that were supported by a system of slings, cables and a trolley that was controlled by the subjects as they performed maneuvers. The facility also studied astronaut fatigue limit and energy expenditure in the one-sixth Earth-gravity conditions.

was a network of slings and cables. This was attached to a lightweight trolley that travelled freely along an overhead track that was part of the larger Lunar Landing Research Facility.

A number of the Apollo astronauts practiced lunar walking in Langley's Reduced Gravity Simulator.

Aerodynamics and structures research

Many other things were done at Langley to support Apollo. Through hundreds of hours of wind-tunnel testing, researchers helped to determine the aerodynamic characteristics of the Apollo-Saturn launch configuration. In order to evaluate Apollo's ablative heat-shield materials, an electric arc heater was used at Langley that could duplicate the intense heat generated by friction during reentry. In numerous facilities, including the 8-Foot High-Temperature Tunnel, Langley engineers conducted critical investigations into the structural integrity of Apollo.

One of the major research projects managed by NASA Langley in support of Apollo was FIRE (Flight Investigation Reentry Environment). Although this project mainly consisted of flight tests involving Atlas rockets with recoverable reentry packages, FIRE also involved wind-tunnel testing. The purpose of the project was to study the effects of reentry heating on spacecraft materials.

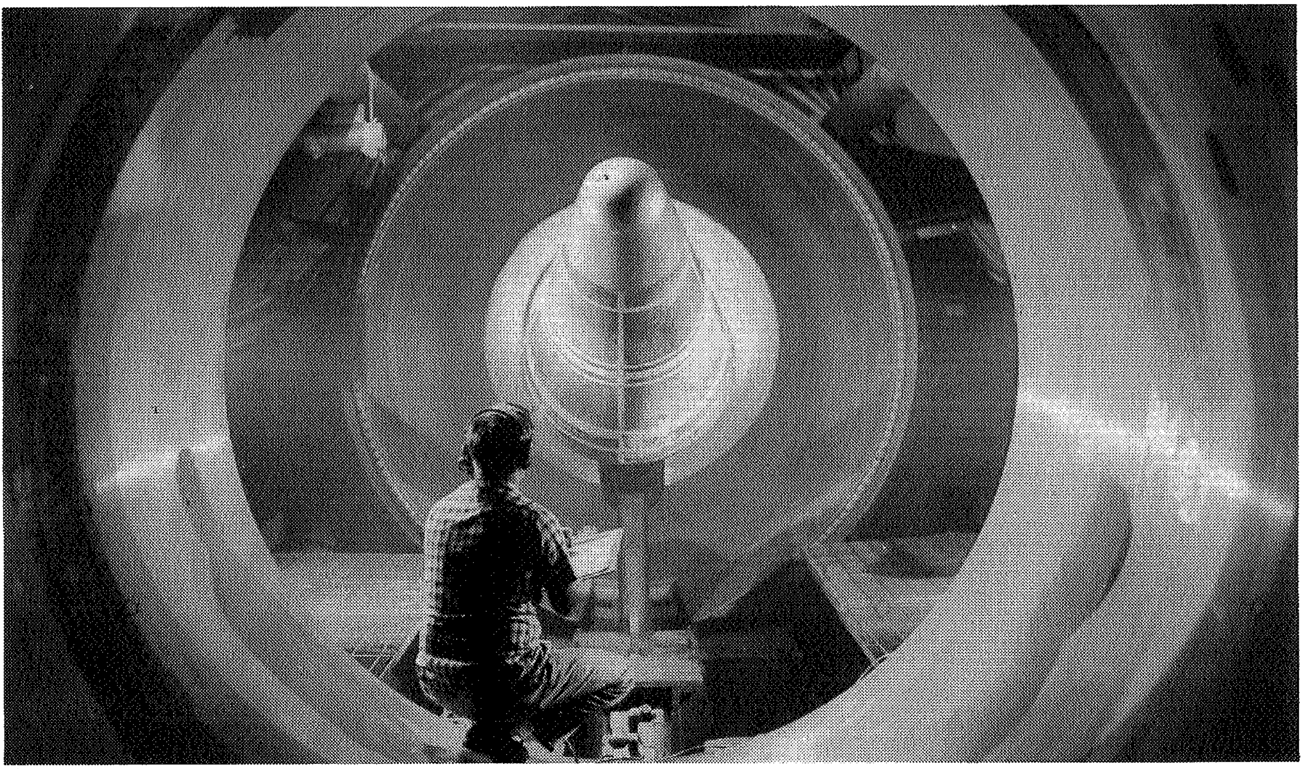
From lunar orbiter tracking data, staff members constructed representations of the moon's gravitational field. These mathematical models proved invaluable in the design and timing of critical operating maneuvers during the flight of Apollo 11 and the subsequent lunar landing missions.

Conclusion

This discussion only summarizes the highpoints of Langley's contributions to the Apollo lunar landing and exploration program. As President Kennedy indicated, the entire nation would have to go to work if Americans were to set foot on the moon by the end of 1969.

No place was more fortunate to participate in the achievement of the lunar objective than was the Langley Research Center.

"Langley's Contributions to the Apollo Program" was prepared by the NASA Langley Research Center Office of Public Affairs.



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The effects of reentry heating on the Apollo spacecraft were tested in the 8-foot High-Temperature Structures Tunnel at Langley.

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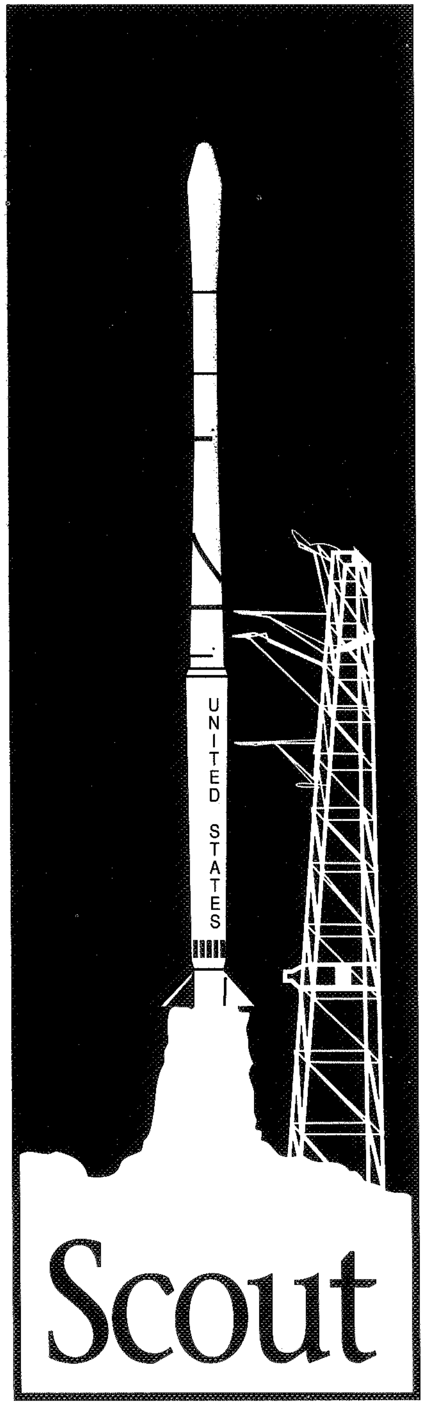

Scout Launch Vehicle Program

Since 1959, NASA's Langley Research Center in Hampton, Virginia, has managed one of the nation's most successful and reliable launch vehicles, known as Scout. Scout, an acronym for Solid Controlled Orbital Utility Test system, is a four-stage solid fuel satellite system capable of launching a 385-pound satellite into a 500-mile orbit. There have been 114 Scout launches, and its overall 96 percent success rate has earned this workhorse a spot in the National Air and Space Museum, where it stands beside other veterans of America's space program, such as Jupiter, Aerobee and Vanguard rockets. Scout's honor roll includes 23 satellites launched for international space organizations. Payloads have been launched for the European Space Research Organization, for Germany, for the Netherlands, for France, for Italy, and for the United Kingdom. Through the years, Scout has launched 94 orbital missions, (27 Navy navigational and 67 scientific satellites), seven probe missions and 12 reentry missions.

On January 1, 1991, after more than 30 years, NASA Langley transferred the management of the Scout Project to the NASA Goddard Space Flight Center, Greenbelt, Maryland.

Those who have worked on the Scout program have made a unique contribution to the U.S. space program. They have created a launch vehicle system that set a standard for simplicity, productivity and reliability. They did it by establishing uncompromising standards of exactness and by an unwavering pursuit of excellence. In these accomplishments, they created an atmosphere of teamwork and mutual respect that those who worked on Scout will never forget.

The Scout team has consisted not only of NASA Langley employees but a group of employees from the LTV Missiles and Electronics Group of Dallas, prime contractor for the development of Scout systems. In 1959, Langley Research Center awarded the contract to LTV to develop the airframe and launcher. This began a partnership between NASA Langley and LTV that has lasted for over thirty years. Scout's reliability stems from a sense of teamwork and cooperation between government agency and contractor. Together, these people shared success and failure—some of whom spent an entire career on the project. Ultimately, Scout is a vehicle that proved itself, over and over, to be reliable and dependable.

Scout's reliability also stems from standardized procedures and configuration control and from its simple, old-fashioned technology. The vehicle was built with off-the shelf hardware. Designers selected from an inventory of solid-fuel rocket motors produced for military programs: the first stage motor was a combination of the Jupiter Senior and the Navy Polaris; the second stage came from the Army Sergeant; and the third and fourth stage motors were designed by Langley engineers who adapted a version of the Navy Vanguard. The heatshield and fins are insulated with cork. The guidance system uses simple gryos that cannot be reprogrammed after launch. But this old-fangled technology makes Scout reliable and predictable.

Since its early development, the configuration of Scout has continued to evolve. Each of the motors has been upgraded at least twice, and improvements in rocket engine design have enabled the rocket to carry larger payloads. Even so, the current Scout G-1 configuration is very similar in appearance to that of the original vehicle—a testimony to the soundness of the original design.

Scout is 76 feet long, 45 inches in diameter and weighs 48,600 pounds. Its four solid propulsion rockets are joined by transition sections containing guidance, ignition, spin up motors and separation instrumentation necessary for flight.

The first stage is the Algol. It is 30 feet long and 45 inches in diameter. The motor burns for an average of 82 seconds with a maximum thrust of 140,000 pounds. At the bottom of this motor are the first stage altitude control jet vanes and fin tips, which steer the vehicle during initial launch.

The second stage, Castor, is 20 feet long and 30 inches in diameter. This stage fires for 41 seconds and develops 60,000 pounds of thrust.

Stage three rocket motor, the Antares, is 10 feet long and 30 inches in diameter. It burns for 48 seconds at 18,000 pounds of thrust. The second and third stage control is provided by hydrogen peroxide jets.

The fourth stage, Altair, is a mere five feet long and 20 inches in diameter. It burns for 34 seconds and develops 6000 pounds of thrust. Its control is provided by spin stabilization.

The heat shield covering the fourth stage and payload section is made of cork and fiberglass laminate. Launch sites for this nation's workhorse are located at the NASA Wallops Flight Facility, Wallops Island, Virginia; at the Western Test Range, Vandenberg Air Force Base, California; and at Kenya, Africa.

The NASA space program has given us images that have become imprinted on the national consciousness as icons of success. Here is one more to consider: our nation's workhorse—Scout.

NASA Langley Research Center
Hampton, Virginia 23665
(804) 864-6122

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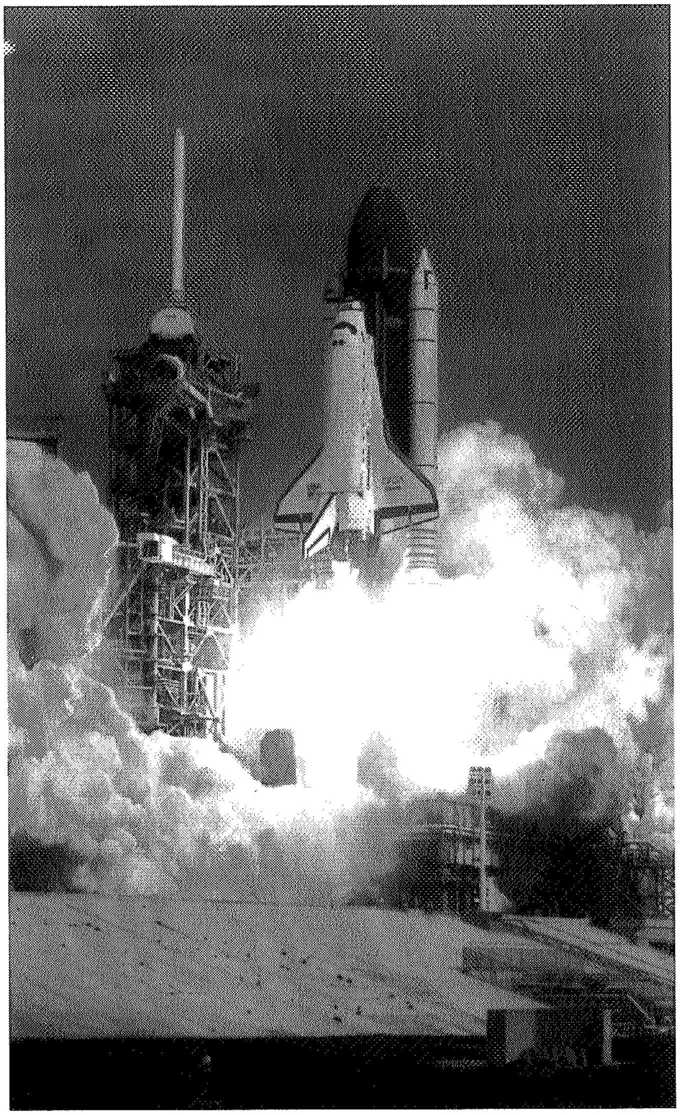
NASA Langley Research Center Contributions to Space Shuttle Program



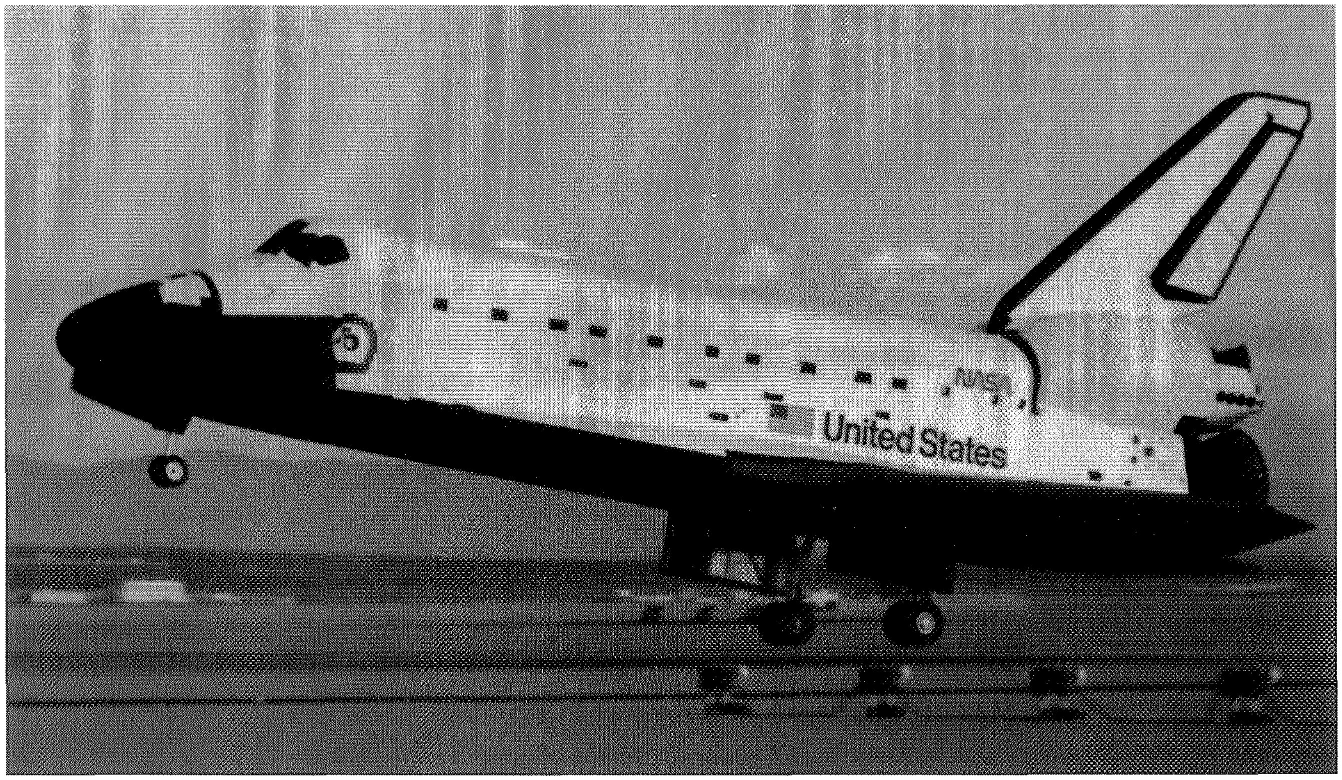
Fact Sheet

Building on its strong tradition of research into the performance of winged flying vehicles as well as pioneering work on hypersonic gliders, the X-15 rocket plane, and other types of "space planes," Langley made vital contributions to NASA's Space Shuttle program. In fact, Langley:

- Contributed to the technology base for a reusable space vehicle and developed preliminary Shuttle designs
- Recommended modified delta wing for vehicle rather than conventional straight wing
- Conducted wind tunnel tests (60,000 wind tunnel hours) and analysis; over one-half of the Aerodynamic Design Data Book came from Langley wind tunnel test results
- Conducted structures and materials tests to determine the requirements for various areas of the vehicle
- Investigated and certified the Thermal Protection System for launch environment
- Performed independent design, analyses and simulation studies to solve problems on the Orbiter flight control and guidance systems
- Conducted landing tests on Shuttle main and nose gear tires and brake systems

- Conducted runway surface texture tests and recommended Kennedy runway modifications
- Participated in the redesign of solid rocket booster components
- Examined launch abort and crew bailout capabilities
- Defined ascent aerodynamic wing loads

Langley's involvement with the Space Shuttle does not end with the improvements to the vehicle, but continues through using the vehicle as transportation into orbit or as a testbed for Langley-developed experiments, such as the Orbiter Experiments, the Assembly Concept for Construction of Erectable Space Structures (ACCESS), the Long Duration Exposure Facility (LDEF), and the Crew Equipment Translation Aid (CETA).



For more information contact:
Public Affairs
Mail Stop 115
NASA Langley Research Center
Hampton, Virginia 23665-5225
804-864-6124

March 1992

69 Months in Space:

A History of the First LDEF (Long Duration Exposure Facility)

When Space Shuttle *Challenger* placed the Long Duration Exposure Facility (LDEF) into orbit on April 7, 1984, the space age was already over a quarter-century old. Satellites had proliferated in number and purpose, men and women had lived and worked in space, manned missions had visited the Moon, and unmanned missions had ventured far into the solar system. By 1984, the Shuttle was beginning to change the character of space operations, and new national goals for space were being defined. This was the context for the flight of LDEF.

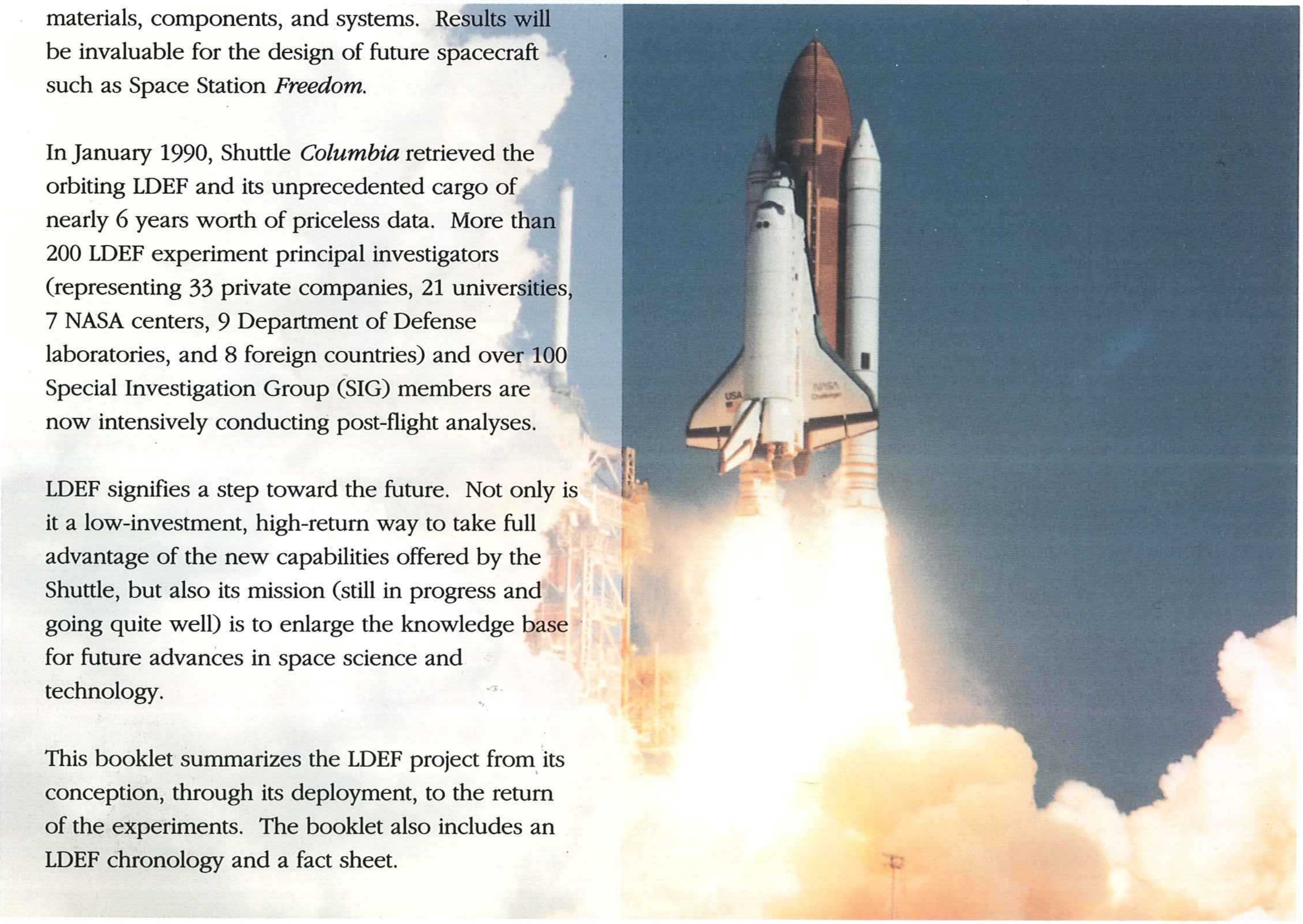
Fifty-seven space experiments, self-contained in 86 desktop-sized, open trays, were arrayed checkerboard-style around the surface of LDEF. These experiment trays faced outward from both ends and all 12 sides of the 11-ton, 30-foot-long, nearly cylindrical satellite.

The experiments carried more than 10,000 specimens to gather scientific data and to test the effects of long-term space exposure on spacecraft materials, components, and systems. Results will be invaluable for the design of future spacecraft such as Space Station *Freedom.*

In January 1990, Shuttle *Columbia* retrieved the orbiting LDEF and its unprecedented cargo of nearly 6 years worth of priceless data. More than 200 LDEF experiment principal investigators (representing 33 private companies, 21 universities, 7 NASA centers, 9 Department of Defense laboratories, and 8 foreign countries) and over 100 Special Investigation Group (SIG) members are now intensively conducting post-flight analyses.

LDEF signifies a step toward the future. Not only is it a low-investment, high-return way to take full advantage of the new capabilities offered by the Shuttle, but also its mission (still in progress and going quite well) is to enlarge the knowledge base for future advances in space science and technology.

This booklet summarizes the LDEF project from its conception, through its deployment, to the return of the experiments. The booklet also includes an LDEF chronology and a fact sheet.



Early LDEF Concept

Although LDEF ultimately accommodated a broad range of scientific and technological interests, including measurements of the meteoroid environment in space, it was first conceived solely as a Meteoroid and Exposure Module (MEM). NASA Langley Research Center in Hampton, Virginia, proposed MEM in 1970 as the first Shuttle payload.

The need for information about the meteoroid environment in space is as old as spaceflight itself; in fact, micrometeoroids had been an object of study as early as 1959 in the Vanguard experiments, America's first scientific satellite program. During the 1960's and 1970's, additional meteoroid work in space gave scientists experimentation experience that proved invaluable for LDEF.

Astronaut Donn F. Eisele beside a mockup of LDEF's early-1970's conceptual forerunner, the Meteoroid and Exposure Module.

One early method for measuring meteoroid impacts was the pressurized-cell detector, in which a sensor would read and report the loss of pressure that resulted from penetration of the space-exposed surface of the cell. Different cells had different skin thicknesses, which were pre-calibrated in ground tests to indicate different penetrating masses. Data transmission equipment relayed information about impacts and penetrations to Earth.

Another method that evolved was the capacitor detector, in which each penetration generated an electrical signal. Meteoroid researchers also studied the "bumper" concept, a shielding technique in which a thin, external sheet of material causes a penetrating object to break up and spread out as debris over a larger area, reducing the likelihood of spacecraft penetration.

These space research activities evolved largely for the benefit of spacecraft designers, who needed a clearer understanding of the hazards that meteoroids imposed. The story of MEM/LDEF is in part the story of efforts to achieve this understanding. Research techniques were also evolving for other areas of space study, and LDEF would ultimately accommodate those as well.

MEM was foreseen as a cylinder sized for the Shuttle's payload bay. The Shuttle would place it in orbit, where its large surface area would collect a comprehensive sample of meteoroid data. MEM was to include thick-skin, thin-skin, and bumper configurations. After several months, the Shuttle would retrieve MEM and bring it to Earth for data analysis. This retrievability feature, both for MEM and for LDEF, was especially important.

In almost all previous space research, the only measurements available were those that could be transmitted to Earth. Data transmission equipment was expensive, took precious room in a spacecraft, and was not always absolutely reliable. Retrievability eliminated the need for this equipment for the MEM or LDEF. Retrievability also placed hard experimental evidence, not just transmitted signals, into researchers' hands. This evidence allowed in-depth analysis, use of a variety of analytical equipment, and participation by an increased number of investigators.

As important as the developing field of meteoroid research was, it could not obscure the attractiveness of a retrievable, MEM-type experimentation vehicle for many other kinds of space research.

In 1974, MEM was renamed LDEF, and LDEF officially became a NASA project managed by Langley Research Center for the Office of

Aeronautics and Space Technology (now the Office of Aeronautics, Exploration and Technology). Meteoroid research was still seen as the primary mission. Eventually, however, what had begun as a concept for meteoroid research was to become a vehicle also meant for:

- studies of changes to physical properties of materials over time in the space environment,
- performance tests of spacecraft systems,
- evaluations of components used in powering spacecraft,
- experiments in the growth of crystals in low gravity, and
- scientific investigations in space physics and related fields.

By early 1990, science and technology investigators around the world would be hard at work analyzing the results.

The LDEF Spacecraft

Besides the advantages of retrievability, LDEF offers:

Simplicity. LDEF is a passive and potentially reusable spacecraft. Complex power, positioning, and data acquisition systems are not required.

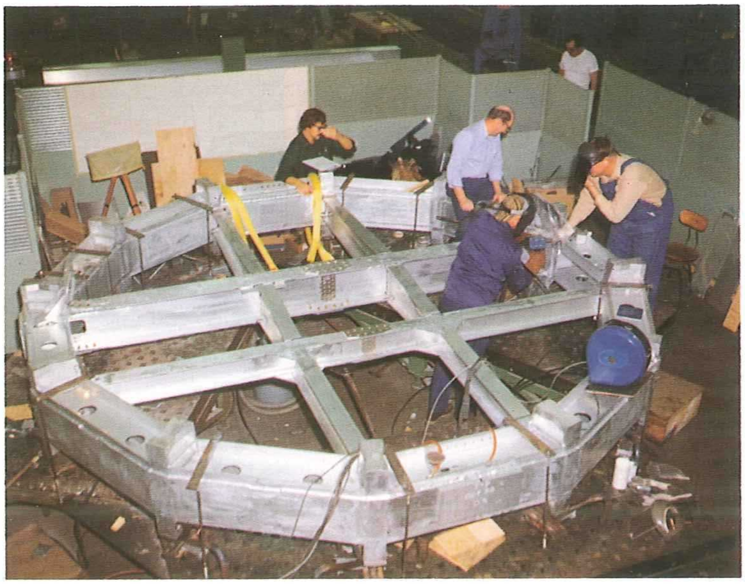
Stability in flight. LDEF has been designed to use gravity to be inherently stable in orbit. Thus, a given experiment keeps a single orientation with respect to the orbit path, for example, facing ahead or facing Earth. Knowledge of an experiment's orbit orientation enhances clear understanding in post-flight data analysis because impacts and other space-environment effects are different for different orientations. This clarity is also enhanced by another result of inherent stability, the constancy of LDEF's drag as it moves through the uppermost traces of the Earth's atmosphere. LDEF's unique passive stability means that it does not need propulsion or maneuvering systems. Without the requirement of attitude control system jet firings, LDEF is virtually free of acceleration forces—a key advantage for certain experiments.

A pristine environment. The liquid and particulate contaminants associated with human presence and the firing of propulsion systems can skew the experiments inside or near manned or maneuvering spacecraft. LDEF travels through space with no crew and no propulsion.

Relaxed space and weight limitations. In typical pre-Shuttle experiments, every ounce or cubic inch was important. LDEF experiments benefit from the Shuttle's large payload bay and tremendous lifting capacity. LDEF experiment trays provide up to about 12 cubic feet of volume, and, if necessary, LDEF can support even larger experiments in its internal structure.

The satellite that provides these advantages for space research was designed and fabricated at Langley in the late 1970's. The nearly cylindrical, mainly aluminum framework provides a grid of spaces for attaching experiment trays and carrying them exposed through the space environment.

In cross section, LDEF has the shape of a dodecagon (a 12-sided regular polygon). The evolution from the earlier MEM cylinder concept gave LDEF its 12 flat sides as a way of accommodating simple, flat experiment trays. The dodecagonal shape is close enough to cylindrical to ensure efficient use of the Shuttle's payload bay.



Fabricating LDEF's center ring frame

At the heart of LDEF is the dodecagonal center ring frame, a comparatively heavy aluminum structure. To ensure the structural integrity of LDEF, the center ring frame welds had to meet extraordinarily high quality control standards. Weld quality was verified by X-rays.

Aluminum beams called longerons connect the center ring frame to the two end frames. With the addition of aluminum intercostals, which connect from longeron to longeron around the 12 sides of the satellite's circumference, the 86-tray framework was complete: 12 longitudinal rows of 6 tray spaces each, with a total of 14 additional tray spaces in the 2 end frames.

Longerons are bolted rather than welded to intercostals and to the center ring and end frames. Thus, by simply replacing the longerons, a shorter or longer LDEF can be easily constructed to meet the payload manifest requirements for a given Shuttle flight.

For overall stiffness, tubular structural members stretch diagonally through the interior of LDEF, connecting the center ring frame with the end frames.

At the center of the space-facing end frame of LDEF is a viscous magnetic damper, a stabilizing device about half the size of a basketball. This damper uses the Earth's magnetic field and a viscous fluid to gradually cancel destabilizing vibrations caused when the Shuttle places LDEF into orbit.

The outer sphere of this damper is rigidly attached to LDEF. Floating concentrically inside it is a second sphere, separated from the outer one by a layer of silicone oil. Rigidly attached inside the inner sphere is a magnet, which tends to keep the inner sphere constantly aligned with the Earth's magnetic field. In turn, flow resistance in the oil tends to quell motions of the outer sphere, thereby damping unwanted vibrations in LDEF.

LDEF just before shipment to Kennedy Space Center

For transport to and from orbit, LDEF rides in the Shuttle payload bay like a battery in a flashlight. Two attachment points on opposite sides of LDEF's center ring frame connect to fixtures in the Shuttle's sides to provide the main support. The third fixture attaches to the payload bay deck, and the fourth fixture, at the center of one end, connects to the

Shuttle via a special beam (called the "walking" beam) which stays with LDEF in orbit.

This attachment system appears simple but actually responds to the complexities of Shuttle operations. The in-flight loads of the 11-ton LDEF must be distributed precisely through the Shuttle structure.

The system also simplifies recovery of LDEF from orbit. Temperature extremes in space can slightly bend or warp LDEF, displacing its attachment points. To ensure a clean fit, the points are distributed about LDEF such that no more than three can touch the Shuttle in any given plane. Just as a three-legged stool can always find stability, LDEF's attachment points can always find their way smoothly into place. The ability of the "walking" beam to rotate slightly provides the needed tolerance.

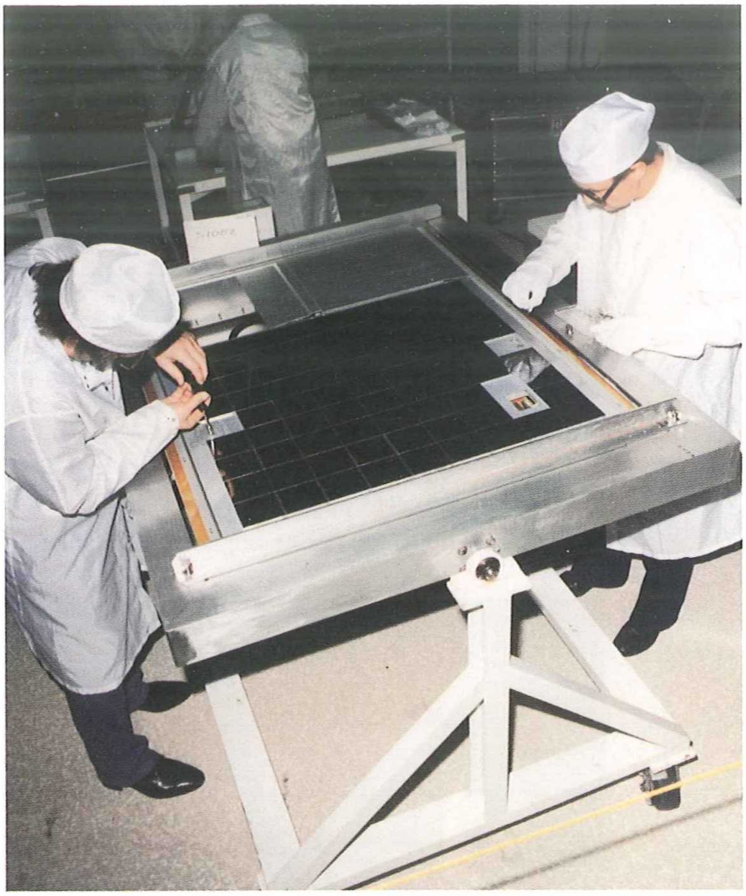
Construction of LDEF began in 1976 and was completed in August 1978. Although it had been designed to be strong enough to preclude the need for extensive structural tests, LDEF underwent flight qualification dynamic and static tests at Langley before being stored in 1979 for use in space via the Shuttle.

Experiments in Trays

Although the technological and scientific questions that LDEF addresses are complex, the LDEF approach to answering them has purposely been kept simple. The LDEF project was designed to minimize logistical, financial, and paperwork burdens on investigators and other project participants.

Such a philosophy continues the motivating spirit of the Shuttle, the space transportation system on which LDEF was predicated. The Shuttle was created to make access to space easier and simpler.

For anyone involved in LDEF, this approach was clear from the beginning. When the opportunity to place experiments aboard LDEF was formally announced to the worldwide technological and scientific community in 1976, the only application documentation required of a prospective investigator was a letter of intent, a single copy of a brief proposal, and the validation of institutional support.



Investigators prepare an experiment tray for installation on LDEF

Later, when experiments had been chosen from among the hundreds of applications submitted, the relationship between NASA and a given experiment team was formalized in a Memorandum of Agreement that was a mere two pages long. With the viability of each chosen experiment already established, NASA thereafter held to a relationship with its LDEF experimenters similar to that of a landlord with a tenant: as long as the safety and physical integrity of LDEF and its experiments were not jeopardized, experiment teams could enjoy independence.

Independence and simplicity extended to the experiment trays as well. With trays, investigators could fully prepare their experiments at their home institutions, ship them to Kennedy Space Center (KSC) for spaceflight, and then ship them home for extensive data analysis. Special covers and shipping containers were fabricated for handling and moving the experiment trays.

Most of the trays are slightly larger than 3 by 4 feet, with depths of 3, 6, or 12 inches. Trays for the two end surfaces on LDEF are about 2 1/2 feet square. Some experiments used more than one tray, and some used only 1/4 or 1/6 of a tray, sharing the remainder with other experiments. Each tray slips into its appointed place in the checkerboard surface pattern of LDEF and is held there by clips which are bolted to the LDEF structural framework.

Although LDEF space research was generally conceived as passive (that is, requiring no power source or data handling capability), many experiments did have modest requirements for active systems. For each experiment that needed to record measurements on tape a few times per day, LDEF used a standard Experiment Power and Data System (EPDS). EPDS, which consists of a data processor controller assembly, a magnetic tape module, and a lithium battery, was designed to offer versatility in accommodating different kinds of data collection needs.

Experiments needing protection from transient environments on the way to and from orbit used a special Experiment Exposure Control Canister. This canister is basically a sealable drawer that is opened and closed by a small electric drive system triggered by a preset timer. The canister opens after deployment into orbit, exposes its experiment to the space environment, then seals the experiment back inside before retrieval.

Studying the Space Environment

The space environment that LDEF experiments study includes radiation, vacuum, extreme temperatures, atomic oxygen, flecks of spacecraft paint, interstellar dust, micrometeoroids, the absence of gravity, etc. The purpose of such study is to enlarge the knowledge base for building future technology, especially the space technology of the next decade.

This enlarged base of knowledge can be useful in several ways. It can improve the materials and design of spacecraft and space equipment, especially structures slated for long stays; it can tell us more about commercial or industrial opportunities in space; and it can validate or suggest modifications to procedures used on Earth to test space materials and systems, thereby increasing confidence in the easier, less expensive, Earthbound tests. For longer term use, it can add to our fundamental understanding about Earth, the nearby reaches of space, and the universe itself.

Some examples of the scientific and technological questions that LDEF experiments address follow:

- *How durable are composite materials in space?* Composite materials (plastics reinforced with high-strength fibers such as fiberglass) are lighter and stronger than metals and are therefore attractive to spacecraft designers.
- *Which thermal coatings work best over time?* Certain paints and other materials used as coatings can passively and effectively counteract the temperature extremes that spacecraft must endure. But radiation, atomic oxygen (individual oxygen atoms), and other space effects can degrade their effectiveness.
- *How can solar cells used in space be improved?* Spacecraft need electricity, and solar cells can use the Sun to generate it, but only by facing the space environment with little or no protection.
- *Which heat pipe concepts work best?* Spacecraft need temperature control. Simple, inexpensive heat pipes can passively manipulate thermal conditions by capitalizing on the natural effects of the zero-gravity environment.
- *Can fiber optic materials find wide use in space?* If radiation and other effects do not prove to be obstacles, space systems can use the advantages of fiber optics: lightness, low requirements for power, and relative immunity to electrical disturbance and interference.

- *What potential does space hold for crystal technology, and how well do crystals hold up in space?*
  Crystals are of great value for integrated circuitry and for compact data storage because they are materials with regularly repeating, internal arrangements of their atoms. Crystals are best produced in extremely low gravity over lengthy periods, which are test conditions offered only by LDEF.

- *What might improve the instruments that are used to observe the Earth's environment from space?*
  Certain thermal detectors on satellites can monitor the Earth's seasons and climates, but the space environment can degrade detector performance, thus resulting in faulty data.

- *How does space affect living things over time?*
  To live and work in space, we have to understand its effects on life. LDEF carried living organisms, including biomolecules, plants, and tomato seeds that were used in recent experiments in schools across the Nation.

- *What can matter from space tell us about the universe?*
  LDEF experiments sampled cosmic dust, interstellar gases, subatomic radiation particles, and the dust of comets.

LDEF's Deployment Into Space

Just as LDEF was built to fit the Shuttle and complement its capabilities, LDEF's deployment and retrieval schedules were repeatedly adjusted to fit the complexities of Shuttle scheduling.

The first Shuttle flight took place in April 1981. Later that year, LDEF was removed from storage, and preparations began for a target launch date initially set for December 1983. Pre-flight structural tests of the satellite were conducted at Langley in 1982. With the Shuttle operational, Johnson Space Center in Houston was able to provide analyses to predict the flight loads that LDEF would have to handle.

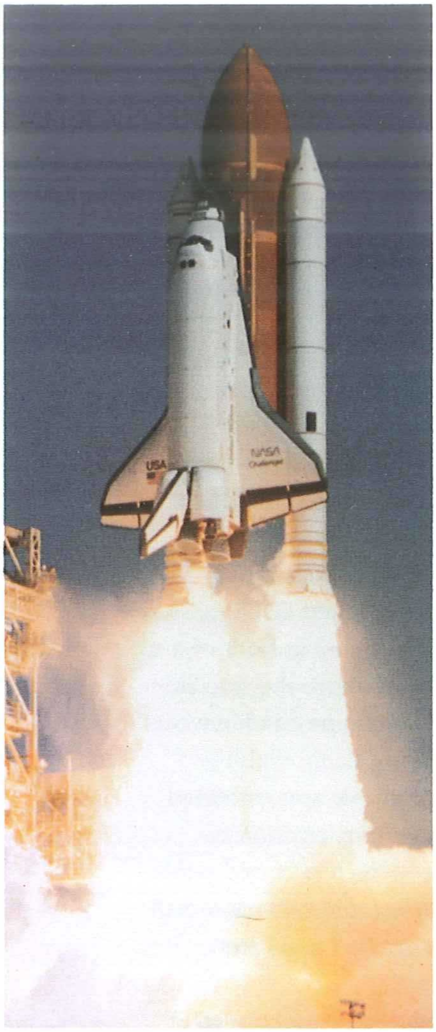
In June 1983, inside a special air-conditioned container, LDEF was shipped aboard a World War II era landing craft to KSC in Florida, where it was placed in SAEF-2, the Spacecraft Assembly and Encapsulation Facility.

Launch was set for April 1984. In November 1983, LDEF project participants from Langley moved to KSC to conduct pre-launch preparations. Experiments had to be received, processed, and fastened into place aboard LDEF.

With its experiments aboard, LDEF then had to be taken through the elaborate pre-launch processing for a Shuttle payload. At KSC's Operations and Checkout (O&C) Building, LDEF was placed into a payload canister for transfer to the launch pad, where it was integrated into Shuttle *Challenger's* cargo bay.

Challenger carried LDEF into space after lifting off from Pad A, Launch Complex 39, at 8:58 a.m. EST (eastern standard time) on April 6, 1984. This STS

LDEF, inside a special container, was shipped to Kennedy Space Center by water in June 1983.



Liftoff of Shuttle Challenger, April 6, 1984, with LDEF aboard

(Space Transportation System) 41C mission was the 11th Shuttle flight.

On *Challenger's* 19th orbit, at a point above the Pacific Ocean near Wake Island, LDEF was deployed at 12:26 p.m. EST on April 7. The orbit was nearly circular at 257 nautical miles and at an inclination to Earth of 28.4 degrees. Everything went as planned.

Relative to Earth, the Shuttle was on its back, at an angle, tail end down during the deployment operation. Relative to its orbit path, *Challenger* was facing rearward. Astronaut Terry Hart used the Shuttle's 50-foot-long remote manipulator arm to engage LDEF and move it out of the payload bay. In the process, a startup signal was sent to electrical systems in the experiments. The space age had never before known a satellite designed to be orbited, brought back to Earth, and used again.

To move away from LDEF, the Shuttle fired small thrusters, causing the relative motion of the two separating spacecraft to change. The separation rate at first was about 1/2 foot per second, and it was raised incrementally to about 5 feet per second.

After leaving LDEF, *Challenger* went on to successfully carry out STS-41C's other main purpose of catching and repairing the Solar Maximum Mission satellite (Solar Max). Solar Max, launched in 1980 with instruments to study the Sun, began to fail after 10 months of operating as planned.

Challenger returned to Earth on April 13, landing at Edwards Air Force Base, California, to end its nearly 7-day mission.

Plans at the time of deployment called for *Challenger* to retrieve LDEF in early February 1985. Later, the schedule was slipped to the fall of 1986 to accommodate other Shuttle scheduling considerations. After *Challenger* was lost in January 1986, all Shuttle launches were suspended, and they did not resume until September 1988.

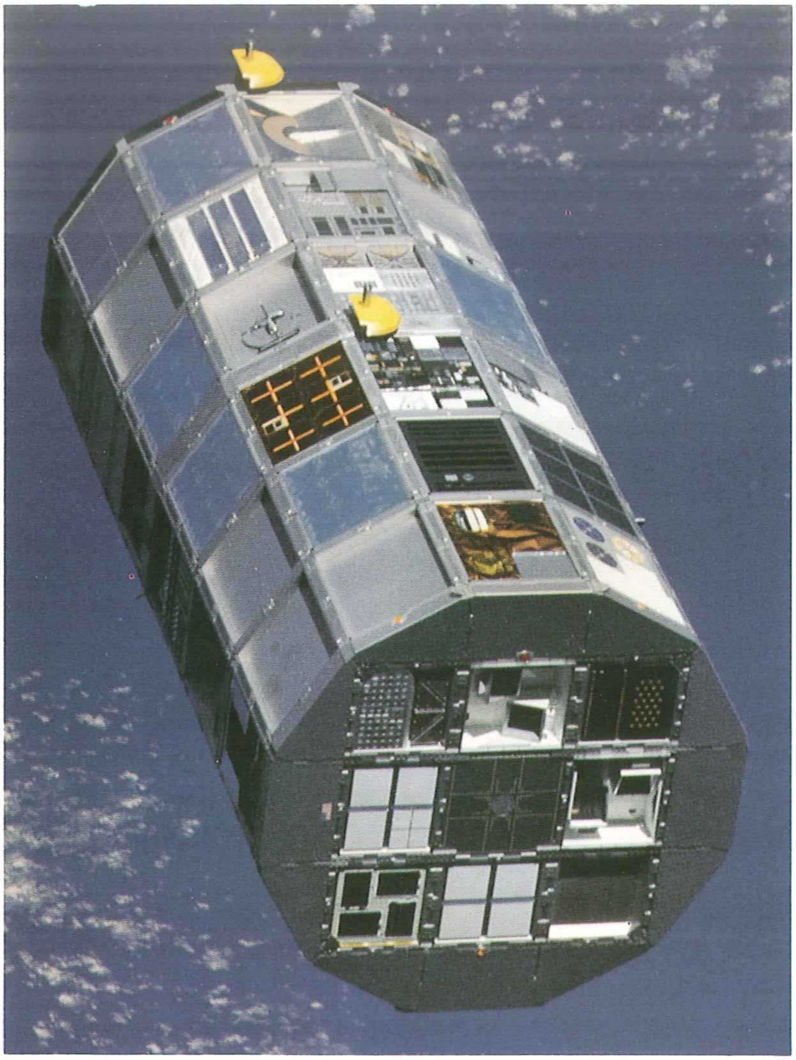
Treasure Trove of Data

LDEF was to remain in orbit for nearly 6 years. Overall, the much-lengthened stay in space actually increased LDEF's technological and scientific value, although it was disadvantageous for some experiments. LDEF's fundamental task, after all, was to gather data on the effects of long-term space exposure. When the satellite was brought back to Earth in early 1990, it had become a treasure trove of information.

Retrieval was some distance in the future when Langley LDEF staff at KSC finished their post-launch work and headed back to Hampton. LDEF's specially configured, wheeled transporter and the experiment shipping containers were put in storage at KSC. Other equipment was sent back to Langley to be saved for post-flight use.

During the mid-1980's, with LDEF in orbit, extensive conceptual planning took place for additional LDEF missions that could re-use LDEF or use a variant of the original LDEF design. LDEF itself, once retrieved, could be varied in length simply by unbolting and replacing its longerons (the longitudinal members in the checkerboard grid) with shorter or longer ones. By September 1985, 42 companies, including 21 with experiments aboard LDEF, had expressed an interest in commercial experiments aboard a future LDEF.

The Shuttle program and therefore LDEF remained on hold through 1987 and into 1988. However, by early 1988, a possibility had arisen that the Sun might endanger LDEF's orbit.



LDEF in orbit with its 57 space-exposure experiments

Solar activity, which goes through cycles of about 11 years, was showing signs it might approach the maximum of past cycles. Increased solar activity would mean increased heating of Earth's outer atmosphere, expanding it and creating more drag for LDEF, which was orbiting in the atmosphere's uppermost reaches. This increased drag would mean a decaying orbit and the prospect of LDEF falling back to Earth in a fiery reentry before a Shuttle could retrieve it.

Unfortunately, solar activity predictions were rough at best. With the resumption of Shuttle operations, LDEF retrieval planning proceeded, factoring in monthly assessments from a panel of experts on solar activity. Radar continued to track LDEF's slowly diminishing altitude through 1989 and into January 1990, when the LDEF retrieval mission (STS-32) ultimately took place.

In a complex balancing act, Shuttle planners had for over 1 year continually weighed the LDEF retrieval as one among many important considerations. For a number of reasons, retrieval launch dates had slipped from July to November to December, before Space Shuttle *Columbia* left Earth on January 9 to bring LDEF home.

On the morning of January 12, *Columbia* approached LDEF, passed below it, then circled in front of it to a point 400 feet above the satellite. *Columbia's* Shuttle payload bay was open and facing Earth, with the remote manipulator arm extended toward LDEF in anticipation of grappling it—which occurred when the gap between the two spacecraft had been narrowed to 35 feet.

This method of approaching LDEF was important for preserving the quality of the satellite's space-exposure data. In fact, the "R-bar" approach set the tone for all that was to come in the handling of the treasure trove of information.

It had long been recognized that in an approach similar to those used in spacecraft-rendezvous operations, the plumes of the Shuttle's maneuvering jets could contaminate LDEF's pristine data. As early as 1978, studies at Langley had suggested the R-bar approach as a way to preclude plume impingement on the open surfaces of the experiments.

When Mission Specialist Bonnie Dunbar grappled LDEF at 9:16 a.m. CST (central standard time) on January 12, the space-environment effects recorded on its experiment surfaces included minimized contamination from *Columbia*.

What followed was the first of many meticulous steps taken to preserve the integrity of the experiment data. For 4 1/2 hours, Dunbar used the remote manipulator arm to turn and maneuver LDEF for an extensive visual inspection and photographic survey of all its surfaces. In this way, any non-space effects caused during LDEF's descent to Earth in *Columbia's* payload bay could be distinguished from the effects meant for study.

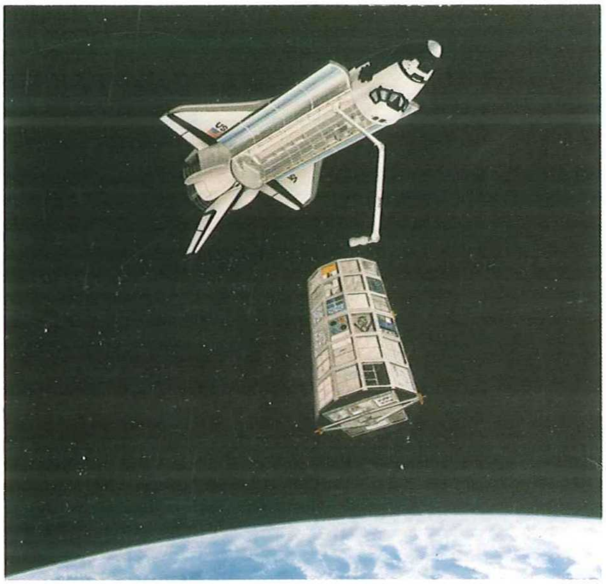
After the photos were all taken, Dunbar berthed LDEF aboard *Columbia.* A few days later, on January 20, *Columbia* touched down at Edwards Air Force Base, California. With LDEF aboard, total Shuttle weight was 115 tons, or 5 tons heavier than any previous Shuttle at landing. The concrete runway had been chosen over the often-used dry lake bed at Edwards for better landing control of the heavily laden Shuttle.

Returning Experiments

Meticulous care to preserve the integrity of experiment data was a defining feature not only in bringing LDEF home, but also in bringing the experiments back to their investigators.

For other Shuttle missions, it was the "prelaunch processing" of payloads that required great attention and effort. In fact, for the retrieval mission itself, preflight payload work had included preparing a Navy communications satellite for Shuttle *Columbia* to launch. But *Columbia* was also to come back from space with LDEF and its 57 experiments, and that meant a new kind of payload concern: postlaunch processing.

Artist's concept of Space Shuttle Columbia retrieving LDEF



With LDEF still inside, *Columbia* was ferried from Edwards to KSC atop an aircraft specially configured for that purpose. Special equipment to help ensure the cleanliness of the atmosphere inside the payload bay had been staged at stops along the way. If the ferry flight had been delayed for any reason, this equipment would have helped continue protecting the experiments from even slight contamination.

A team of LDEF project staff from Langley had arrived at KSC weeks before LDEF's return. Their job was to support the initial stages of postlaunch processing the returning LDEF payload. An international team, including scientists, engineers, technicians, and others, later assumed responsibility for inspecting and photo-documenting the experiments, for seeing to the contamination-free removal of the experiments from LDEF and their return to their investigators' home institutions, and for scrutinizing LDEF itself for information about the space environment.

Columbia arrived at KSC on January 26. A few days later, in KSC's Orbiter Processing Facility, LDEF was lifted out of the payload bay, placed in a special canister, and moved to the Operations and Checkout Building. On February 1, LDEF was placed on its own transporter and turned over to the Langley team. The next day it was moved to SAEF-2, the Spacecraft Assembly and Encapsulation Facility.

In the pristine cleanliness of SAEF-2, LDEF was set up, leveled, and readied to be rotated for access to each individual row of trays. Close inspection and other deintegration preparations took until February 22. During that time, experimenters could examine but not touch their experiments. Special clothing was required for work in the ultra-clean environment in which tray deintegration was about to begin.

An experiment tray is removed from LDEF in SAEF-2 at the Kennedy Space Center.

During deintegration, photo-documentation efforts were intensified. From the time *Columbia* had first grappled LDEF, a photographic record of the sometimes fragile surface conditions of the experiments had been compiled. After the individual trays were removed from the satellite, photographs were taken of all sides of the trays. An area with optimized lighting was set aside and used as a photographic studio.

By March 29, the last tray had been removed, closely inspected by the principal investigators, individually photo-documented, packed, and shipped to its home institution for comprehensive data analysis.

Each tray had been processed through a lengthy checklist of steps. The master schedule for this processing had been continually updated to accommodate the differing time demands for different trays at different stages. This allowed LDEF's monopoly on a portion of KSC's facilities to be kept as brief as possible, and it expedited attainment of the project's goal: the fruitful analysis of LDEF data.

Compared with the originally planned year in orbit, the 5-year, 9-month flight had greatly enhanced the potential value of most LDEF materials, systems, and experiments—especially the comparisons of findings on different areas of the spacecraft. NASA recognized this potential and created four LDEF SIG's (Special Investigative Groups) to address it. The SIG's will provide a unified perspective for spacecraft regarding materials, systems (e.g., seals, fasteners, mechanisms, and canisters), radiation, meteoroids and debris, and contamination.

By March 29, the SIG's had begun this expanded analysis of the LDEF structure and experiment trays so that the combined value of LDEF data to space missions would be assessed and documented.

Even after the trays were gone, the extra-long working days for the Langley LDEF deintegration team continued, lasting through April and into May. LDEF itself needed the same sort of attention that the experiments were going to receive because it too was an experiment. What better way to understand long-duration space-exposure effects on a spacecraft than to bring one home for scrutiny after a long stay in space? The close look at LDEF included a broad range of study from the meteoroid and debris survey of the entire structure to the evaluation of the welds in the center ring frame.

By mid-May, LDEF and its transporter had been stored at KSC, the Langley LDEF team and its equipment were returning to Hampton, and experiment data analysis was well under way at numerous locations around the United States and the world.

LDEF Chronology

1970	Langley proposed conceptual forerunner of LDEF, called Meteoroid and Exposure Module (MEM), to be first Shuttle payload
June 1974	LDEF Project formally under way, managed by Langley for NASA's Office of Aeronautics and Space Technology (OAST)
1976 to August 1978	LDEF structure designed and fabricated at Langley
Summer 1981	LDEF preparations under way for December 1983 target launch date
September 1981	First international meeting of LDEF experimenters held at Langley
1982	LDEF structure tested for ability to withstand Shuttle-induced loads
June 1983	LDEF shipped from Langley to KSC; placed in SAEF-2 (Spacecraft Assembly and Encapsulation Facility)
April 7, 1984	During STS mission 41-C, at 12:26 p.m. EST, Shuttle *Challenger* places LDEF in nearly circular orbit of 257 miles high
March 1985	Planned LDEF retrieval (via STS 51D) deferred to later Shuttle flight
January 1986 to September 1988	LDEF's stay in space extended indefinitely when all Shuttle operations were suspended because of the loss of *Challenger*
1987/1988	Solar activity intensity threatens to accelerate decay of LDEF's orbit and thus influences retrieval planning; retrieval target set for July 1989
June 1989	LDEF retrieval flight date, after slipping from July and then November, set for December 18 launch of Shuttle *Columbia*
December 18, 1989	STS-32 launch postponed until second week of January
January 1990	STS-32 launched January 9; LDEF retrieved 9:16 a.m. CST, January 12; *Columbia* landed at Edwards Air Force Base, California, January 20
January 26, 1990	*Columbia*, with LDEF still in payload bay, returned to KSC via ferry flight from Edwards Air Force Base
January 30 and 31, 1990	LDEF removed from *Columbia* in KSC's Orbiter Processing Facility, placed in a special payload canister, and transported to Operations and Checkout Building
February 1 and 2, 1990	LDEF placed in its special transporter, the LDEF Assembly and Transportation System (LATS), and moved to SAEF-2 for experiment deintegration
February 5 to 22, 1990	Deintegration preparation activities take place, including extensive inspection and photo-documentation
February 23 to March 29, 1990	Trays removed, closely inspected, individually photo-documented, packed, and shipped to home institutions for comprehensive data analysis
April and May, 1990	Deintegration wrap-up, including comprehensive investigation and photo-documentation of the LDEF structure itself

LDEF Fact Sheet

Mission

Long-term study to define the space environment and to investigate the effects of this environment on space operations.

Satellite structure

- Reusable, open-grid, 12-sided (plus 2 ends)
- Designed and built (mainly 6061-T6 aluminum) at NASA Langley Research Center

Dimensions & weight

- 30 feet long, 14 feet in diameter
- 8400 pounds empty
- 21,400 pounds with 86 trays holding 57 experiments

Flight data

- Deployment mission: STS-41C launched April 6, 1984, Shuttle *Challenger*
- LDEF deployed into orbit April 7, 1984
- Orbit altitude near circular at 257 miles; orbit inclination 28.4 degrees
- LDEF total distance traveled: 741,928,837 nautical miles, or 32,422 orbits
- Recovery mission: STS-32 launched January 9,1990, Shuttle *Columbia*
- Retrieved from orbit January 12, 1990
- Landed at Edwards Air Force Base, California, January 20, 1990

Experimental method and apparatus

- Long-term exposure of passive and active test specimens
- Preparation at individual investigators' home institutions
- Post-flight data analysis at home institutions
- Low or no power demands
- Minimal or no data recording requirements
- Leave and retrieve (no data transmitted from orbit)

Technology, applications, and science experiment categories

- Materials, coatings, and thermal systems
- Power and propulsion
- Electronics and optics
- Basic science

Environment for experiments

- Free-flying in low Earth orbit
- Gravity-gradient stabilized (unchanging orientation)
- Passive spacecraft with lowest contamination levels and acceleration forces to date
- Controlled environment pre-deployment and post-retrieval

Experiment trays

- 86 total trays: 72 peripheral (12 sides at 6 per side) and 14 end (6 facing Earth, 8 facing away from Earth)
- Approximate dimensions 3 x 4 feet (peripheral); 2.5 x 2.5 feet (end)
- Depth 3, 6, or 12 inches
- Aluminum construction; capacity up to 200 pounds

Affiliations:

- More than 200 experiment principal investigators from
    - 33 private companies
    - 21 universities
    - 7 NASA centers
    - 9 Department of Defense laboratories
    - 8 foreign countries
- More than 100 other investigators from around the world involved in Special Investigation Groups (SIG's)

The National Advisory Committee for Aeronautics (NACA), was NASA's predecessor agency that became world famous for the quality of its aeronautical research. "In the years 1928-1938 no other institution in the world contributed more to the definition of the modern airplane than the Langley Laboratory of the U.S. National Advisory Committee for Aeronautics," said historian R.K. Smith. These two NACA Technical Reports were reprinted and included in this collection as examples of Langley's work.

Historian James R. Hansen has added a brief introduction to each Technical Report to briefly explain their significance.

"The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel," TR No. 460 by Eastman Jacobs, Kenneth E. Ward and Robert Pinkerton.

"The Requirements for Satisfactory Flying Qualities of Airplanes," TR No. 755 by Robert Gilruth.

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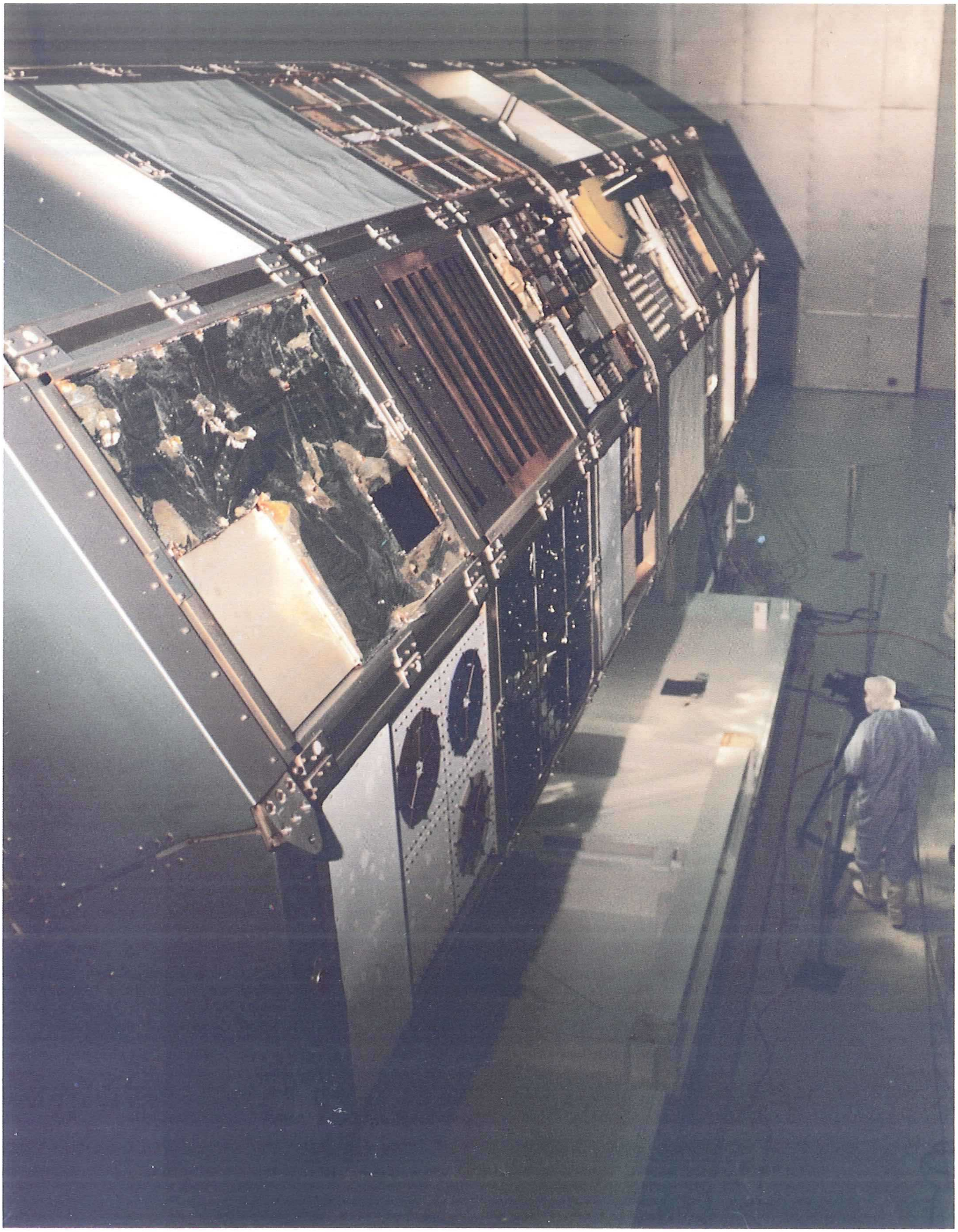

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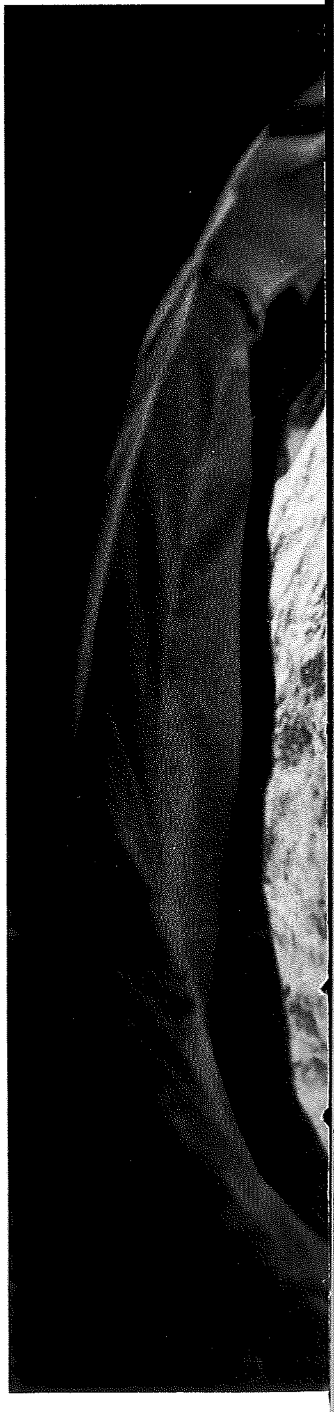

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 460

THE CHARACTERISTICS OF 78 RELATED AIRFOIL SECTIONS FROM TESTS IN THE VARIABLE-DENSITY WIND TUNNEL

By EASTMAN N. JACOBS, KENNETH E. WARD
and ROBERT PINKERTON

1933

For sale by the Superintendent of Documents, Washington, D.C. - Price 15 Cents

Reprinted by NASA Langley Research Center 1992

INTRODUCTION

By

Dr. James R. Hansen

Into the 1920s the airfoil shapes used to design the wings and propellers of the world's aircraft were too various to count, and very little of the airfoil data was uniform. Instead, there existed a hodgepodge, with various national aeronautical establishments employing their own unique series of airfoil shapes: France, its Eifel series; Germany, its Gottingen shapes; Britain, its Royal Aircraft Factory concepts; and the United States, its U.S.A. and Clark series. Beginning in 1923, however, researchers at what was then known as the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics (NACA), NASA's predecessor, began an exhaustive series of tests aimed at rationalizing the airfoil data in terms of "NACA numbers" and coming up with advanced airfoils for much improved aerodynamic performance. The first phase of this testing, which involved both wind-tunnel and flight research, lasted 10 years and culminated in 1933 with the publication of one of the most significant technical reports in aeronautical history: TR 460, "The Characteristics of 78 Related Airfoil Sections From Tests in the Variable-Density Wind Tunnel," by Eastman N. Jacobs, Kenneth E. Ward, and Robert Pinkerton.

The following paper is historically significant in at least three respects. First, all of the data came from Langley's Variable-Density Wind Tunnel, a revolutionary facility of the early 1920s which, by compressing the air to the scale of the model being tested, produced data that corresponded more closely to reality than could any other wind tunnel of that time. Second, the principal author of the paper, Eastman N. Jacobs, became one of the NACA's foremost aerodynamicists; Jacobs would later earn an international reputation by pioneering the development of laminar-flow airfoils and working on a hybrid form of jet propulsion modeled after the Campini ducted fan. Finally and perhaps most significantly, as one of the first papers to announce the results of NACA Langley's systematic airfoil data, the TR 460 created a worldwide sensation among aerodynamicists. The information in the report helped to give birth to a virtual "mail-order catalogue" of airfoils. As one noted aviation historian has written, "no longer did an airplane designer have to hunt and scrape through dozens of obscure publications for the airfoil properties he sought, reworking their data to determine what was desired. The growing catalogue of NACA information had it all, and the properties of available airfoils were reduced to a shelf item." In sum, TR 460 ranks as a classic.

Dr. James R. Hansen is a professor of history at Auburn University and the author of *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1858.*

April 1992

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 460

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By EASTMAN N. JACOBS, KENNETH E. WARD
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For sale by the Superintendent of Documents, Washington, D.C. - Price 15 Cents

AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	kg/m/s		horsepower	hp.
Speed		km/h	k.p.h.	mi./hr.	m.p.h.
		m/s	m.p.s.	ft./sec.	f.p.s.

2. GENERAL SYMBOLS, ETC.

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s^2 $=32.1740$ ft./sec.^{2}

m, Mass $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 760 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m^3 $=0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$.

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o}=\frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force.

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting (relative to thrust line).

Q, Resultant moment.

Ω, Resultant angular velocity.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.

C_p, Center of pressure coefficient (ratio of distance of c. p. from leading edge to chord length).

α, Angle of attack.

ϵ, Angle of downwash.

α_o, Angle of attack, infinite aspect ratio.

α_i, Angle of attack, induced.

α_a, Angle of attack, absolute. (Measured from zero lift position.)

γ Flight path angle.

REPORT No. 460

THE CHARACTERISTICS OF 78 RELATED AIRFOIL SECTIONS FROM TESTS IN THE VARIABLE-DENSITY WIND TUNNEL

By EASTMAN N. JACOBS, KENNETH E. WARD
and ROBERT M. PINKERTON
Langley Memorial Aeronautical Laboratory

1933

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NAVY BUILDING, WASHINGTON, D.C.

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REPORT No. 460

THE CHARACTERISTICS OF 78 RELATED AIRFOIL SECTIONS FROM TESTS IN THE VARIABLE-DENSITY WIND TUNNEL

By Eastman N. Jacobs, Kenneth E. Ward, and Robert M. Pinkerton

SUMMARY

An investigation of a large group of related airfoils was made in the N.A.C.A. variable-density wind tunnel at a large value of the Reynolds Number. The tests were made to provide data that may be directly employed for a rational choice of the most suitable airfoil section for a given application. The variation of the aerodynamic characteristics with variations in thickness and mean-line form were therefore systematically studied.

The related airfoil profiles for this investigation were developed by combining certain profile thickness forms, obtained by varying the maximum thickness of a basic distribution, with certain mean lines, obtained by varying the length and the position of the maximum mean-line ordinate. A number of values of these shape variables were used to derive a family of airfoils. For the purposes of this investigation the construction and tests were limited to 68 airfoils of this family. In addition to these, several supplementary airfoils have been included in order to study the effects of certain other changes in the form of the mean line and in the thickness distribution.

The results are presented in the standard graphic form representing the airfoil characteristics for infinite aspect ratio and for aspect ratio 6. A table is also given by means of which the important characteristics of all the airfoils may be conveniently compared. The variation of the aerodynamic characteristics with changes in shape is shown by additional curves and tables. A comparison is made, where possible, with thin-airfoil theory, a summary of which is presented in an appendix.

INTRODUCTION

The forms of the airfoil sections that are in common use today are, directly or indirectly, the result of investigations made at Göttingen of a large number of airfoils. Previously, airfoils such as the R.A.F. 15 and the U.S.A. 27, developed from airfoil profiles investigated in England, were widely used. All these investigations, however, were made at low values of the Reynolds Number; therefore, the airfoils developed may not be the optimum ones for full-scale application. More recently a number of airfoils have been tested in the variable-density wind tunnel at values of the Reynolds Number approaching those of flight (reference 1) but, with the exception of the M-series and a series of propeller sections, the airfoils have not been systematically derived in such a way that the results could be satisfactorily correlated.

The design of an efficient airplane entails the careful balancing of many conflicting requirements. This statement is particularly true of the choice of the wing. Without a knowledge of the variations of the aerodynamic characteristics of the airfoil sections with the variations of shape that affect the weight of the structure, the designer cannot reach a satisfactory balance between the many conflicting requirements.

The purpose of the investigation reported herein was to obtain the characteristics at a large value of the Reynolds Number of a wide variety of related airfoils. The benefits of such a systematic investigation are evident. The results will greatly facilitate the choice of the most satisfactory airfoil for a given application and should eliminate much routine airfoil testing. Finally, because the results may be correlated to indicate the trends of the aerodynamic characteristics with changes of shape, they may point the way to the design of new shapes having better characteristics.

Airfoil profiles may be considered as made up of certain profile-thickness forms disposed about certain mean lines. The major shape variables then become two, the thickness form and the mean-line form. The thickness form is of particular importance from a structural standpoint. On the other hand, the form of the mean line determines almost independently some of the most important aerodynamic properties of the airfoil section, e.g., the angle of zero lift and the pitching-moment characteristics.

The related airfoil profiles for this investigation were derived by changing systematically these shape variables. The symmetrical profiles were defined in terms of a basic thickness variation, symmetrical airfoils of varying thickness being obtained by the application of factors to the basic ordinates. The cambered profiles were then developed by combining these thickness forms with various mean lines. The mean lines were obtained by varying the camber and by varying the shape of the mean line to alter the position of the maximum mean-line ordinate. *The maximum ordinate* *of the mean line is referred to throughout this report as the camber of the airfoil and the position of the maximum ordinate of the mean line as the position of the camber. An airfoil, produced as described above, is designated by a number of four digits: the first indicates the camber in percent of the chord; the second, the position of the camber in tenths of the chord from the leading edge; and the last two, the maximum thickness in percent of the chord.* Thus the N.A.C.A. 2315 airfoil has a maximum camber of 2 percent of the chord at a position 0.3 of the chord from the leading edge, and a maximum thickness of 15 percent of the chord; the N.A.C.A. 0012 airfoil is a symmetrical airfoil having a maximum thickness of 12 percent of the chord.

In addition to the systematic series of airfoils, several supplementary airfoils have been included in order to study the effects of a few changes in the form of the mean line and in the thickness distribution.

Preliminary results which have been published include those for 12 symmetrical N.A.C.A. airfoils, the 00 series (reference 2) and other sections having different nose shapes (reference 3); and those for 42 cambered airfoils, the 43 and 63 series (reference 4), the 45 and 65 series (reference 5), the 44 and 64 series (reference 6), and the 24 series (reference 7).

The tests were made in the variable-density wind tunnel of the National Advisory Committee for Aeronautics during the period from April 1931 to February 1932.

DESCRIPTION OF AIRFOILS

Well-known airfoils of a certain class including the Göttingen 398 and the Clark Y, which have proved to be efficient, are nearly alike when their camber is removed (mean line straightened) and they are reduced to the same maximum thickness. A thickness variation similar to that of these airfoils was therefore chosen for the development of the N.A.C.A. airfoils. An equation defining the shape was used as a method of producing fair profiles.

If the chord is taken along the x axis from 0 to 1, the ordinates y are given by an equation of the form

$$\pm y = a_0\sqrt{x} + a_1x + a_2x^2 + a_3x^3 + a_4x^4$$

The equation was adjusted to give the desired shape by imposing the following conditions to determine the constants:

(1) Maximum ordinate 0.1 at 0.3 chord

$$x = 0.3 \qquad y = 0.1 \qquad dy/dx = 0$$

(2) Ordinate at trailing edge

$$x = 1 \qquad y = 0.002$$

(3) Trailing-edge angle

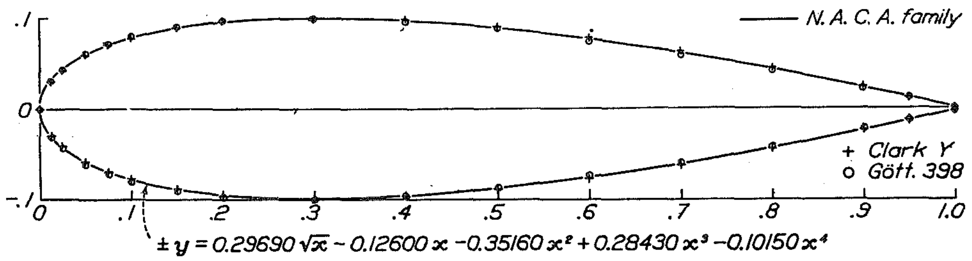
$$x = 1 \qquad dy/dx = -0.234$$

(4) Nose shape

$$x = 0.1 \qquad y = 0.078$$

The following equation satisfying approximately the above-mentioned conditions represents a profile having a thickness of approximately 20 percent of the chord.

$$\pm y = 0.29690\sqrt{x} - 0.12600x - 0.35160x^2 + 0.28430x^3 - 0.10150x^4$$



Basic ordinates of N.A.C.A. family airfoils (percent of chord)

Sta.	0	1.25	2.5	5.0	7.5	10	15	20	25	30	40	50	60	70	80	90	95	100
Ord.	0	3.157	4.358	5.925	7.000	7.805	8.909	9.563	9.902	10.003	9.672	8.823	7.606	6.107	4.372	2.413	1.344	0.210

L.E. radius, 4.40.

FIGURE 1.—Thickness variation.

This equation was taken to define the basic section. The basic profile and a table of ordinates are given in figure 1. Points obtained by removing the camber from the Göttingen 398 and the Clark Y sections, and applying a factor to the ordinates of the resulting thickness curves to bring them to the same maximum thickness, are plotted on the above figure for comparison. Sections having any desired maximum thickness were obtained by multiplying the basic ordinates by the proper factor; that is

$$\pm y_t = \frac{t}{0.20}(0.29690\sqrt{x} - 0.12600x - 0.35160x^2 + 0.28430x^3 - 0.10150x^4)$$

where t is the maximum thickness. The leading-edge radius is found to be

$$r_t=\frac{1}{2}\left(\frac{t}{0.20}a_0\right)^2=1.10t^2$$

When the mean lines of certain airfoils in common use were reduced to the same maximum ordinate and compared it was found that their shapes were quite different. It was observed, however, that the range of shapes could be well covered by assuming some simple shape and varying the maximum ordinate and its position along the chord. The mean line was, therefore, arbitrarily defined by two parabolic equations of the form

$$y_c=b_0+b_1x+b_2x^2$$

where the leading end of the mean line is at the origin and the trailing end is on the x axis at $x=1$. The values of the constants for both equations were then expressed in terms of the above variables; namely,

(1) Mean-line extremities

$$x=0 \qquad y_c=0$$
$$x=1 \qquad y_c=0$$

(2) Maximum ordinate of mean line

$x=p$ (position of maximum ordinate)

$y_c=m$(maximum ordinate)

$$dy_c/dx=0$$

The resulting equations defining the mean line then became

$$y_c=\frac{m}{p^2}[2px-x^2]$$

(forward of maximum ordinate)

and

$$y_c=\frac{m}{(1-p)^2}[(1-2p)+2px-x^2]$$

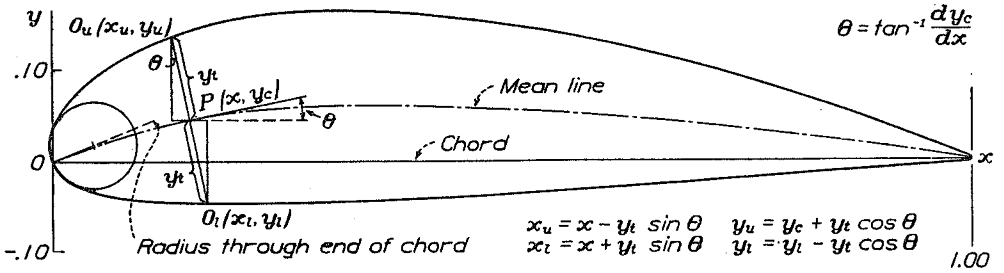
(aft of maximum ordinate)

The method of combining the thickness forms with the mean-line forms is best described by means of the diagram in figure 2. The line joining the extremities of the mean line is chosen as the chord. Referring to the diagram, the ordinate y_t of the thickness form is measured along the perpendicular to the mean line from a point on the mean line at the station along the chord corresponding to the value of x for which y_t was computed. The resulting upper and lower surface points are then designated:

Stations x_u and x_l
Ordinates y_u and y_l

where the subscripts u and l refer to upper and lower surfaces, respectively. In addition to these symbols, the symbol θ is employed to designate the angle between the tangent to the mean line and the x axis. This angle is given by

$$\theta=\tan^{-1}\frac{dy_c}{dx}$$



Sample calculations for derivation of N.A.C.A. 6321

x	y_t	y_c	$\tan\theta$	$\sin\theta$	$\cos\theta$	$y_t\sin\theta$	$y_t\cos\theta$	x_u	y_u	x_l	y_l
0	0	0	[1] 0.40000	0.37140	0.92840	0	0	------	------	0	0
0.01250	0.03314	0.00489	.38333	.35793	.93375	0.01186	0.03094	0.00064	0.03583	0.02436	−0.02605
.30000	.10503	.06000	0	0	1	0	.10503	.30000	.16503	.30000	−.04503
.60000	.07986	.04898	−.07347	−.07327	.99731	−.00585	.07965	.60585	.12863	.59415	−.03067
1	.00221	0	−.17143	−.16897	.98562	−.00037	.00218	1.00037	.00218	.99963	−.00218

[1] Slope of radius through end of chord.

FIGURE 2.—Method of calculating ordinates of N.A.C.A. cambered airfoils.

The following formulas for calculating the ordinates may now be derived from the diagram:

$$x_u=x-y_t\sin\theta$$
$$y_u=y_c+y_t\cos\theta$$
$$x_l=x+y_t\sin\theta$$
$$y_l=y_c-y_t\cos\theta$$

Sample calculations are given in figure 2. The center for the leading-edge radius is placed on the tangent to the mean line at the leading edge.

A family of related airfoils was derived in the manner described. Seven values of the maximum thickness, 0.06, 0.09, 0.12, 0.15, 0.18, 0.21, and 0.25; four values of the camber, 0.00, 0.02, 0.04, and 0.06; and six values of the position of the camber, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 were used to derive the related sections of this family. The profiles of the airfoils derived are shown collectively in figure 3.

For the purposes of this investigation the construction and tests were limited to 68 of the airfoils. Tables of ordinates at the standard stations are given in the figures presenting the aerodynamic characteristics. These ordinates were obtained graphically from the computed ordinates for all but the symmetrical sections. Two sets of trailing-edge ordinates are given. Those inclosed by parentheses, which are given to facilitate construction, represent ordinates to which the surfaces are faired. In the construction of the models the trailing edges were rounded off.

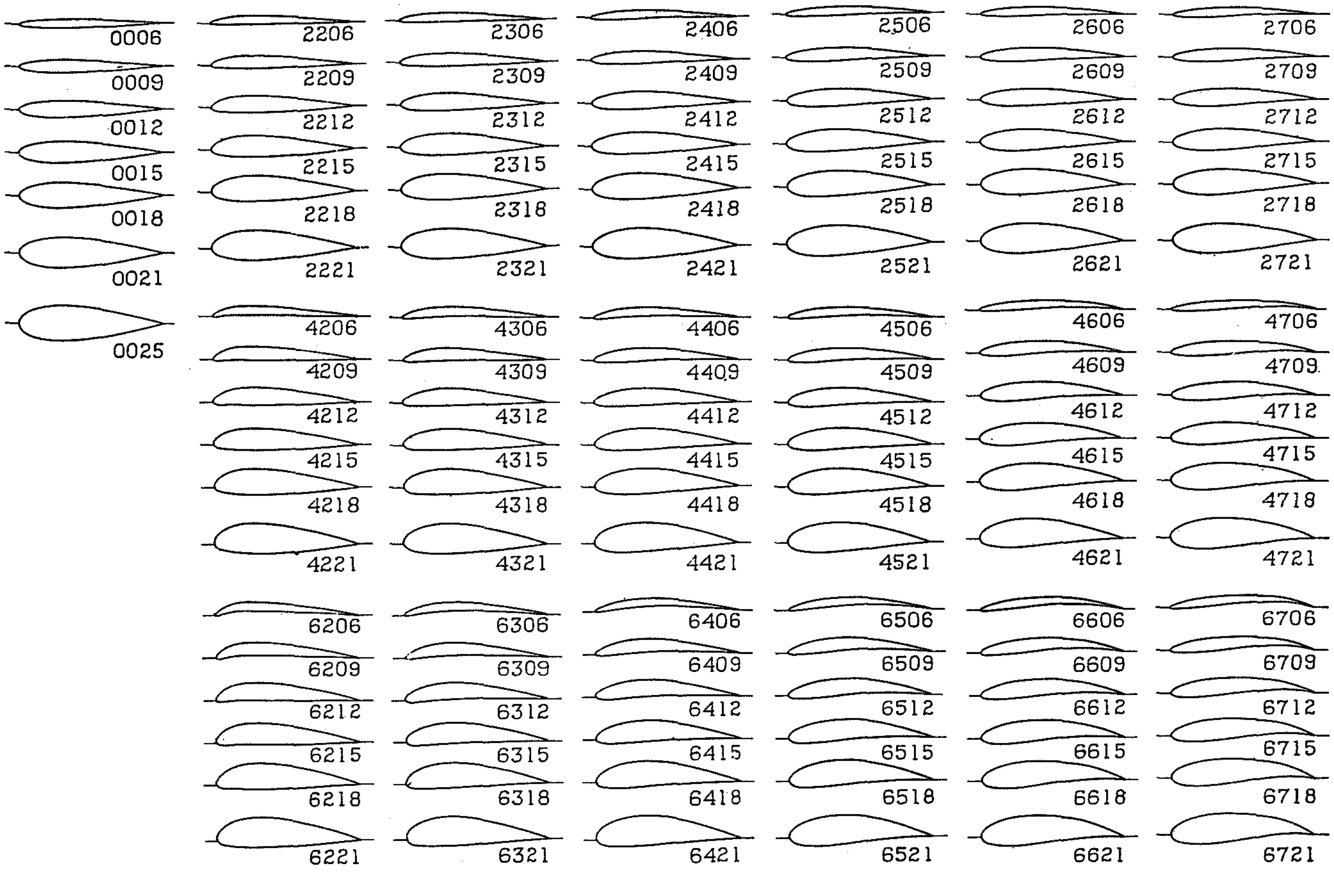


FIGURE 3.—N.A.C.A. airfoil profiles.

Three groups of supplementary airfoils were also constructed and tested. The derivation of these airfoils will be considered later with the discussion.

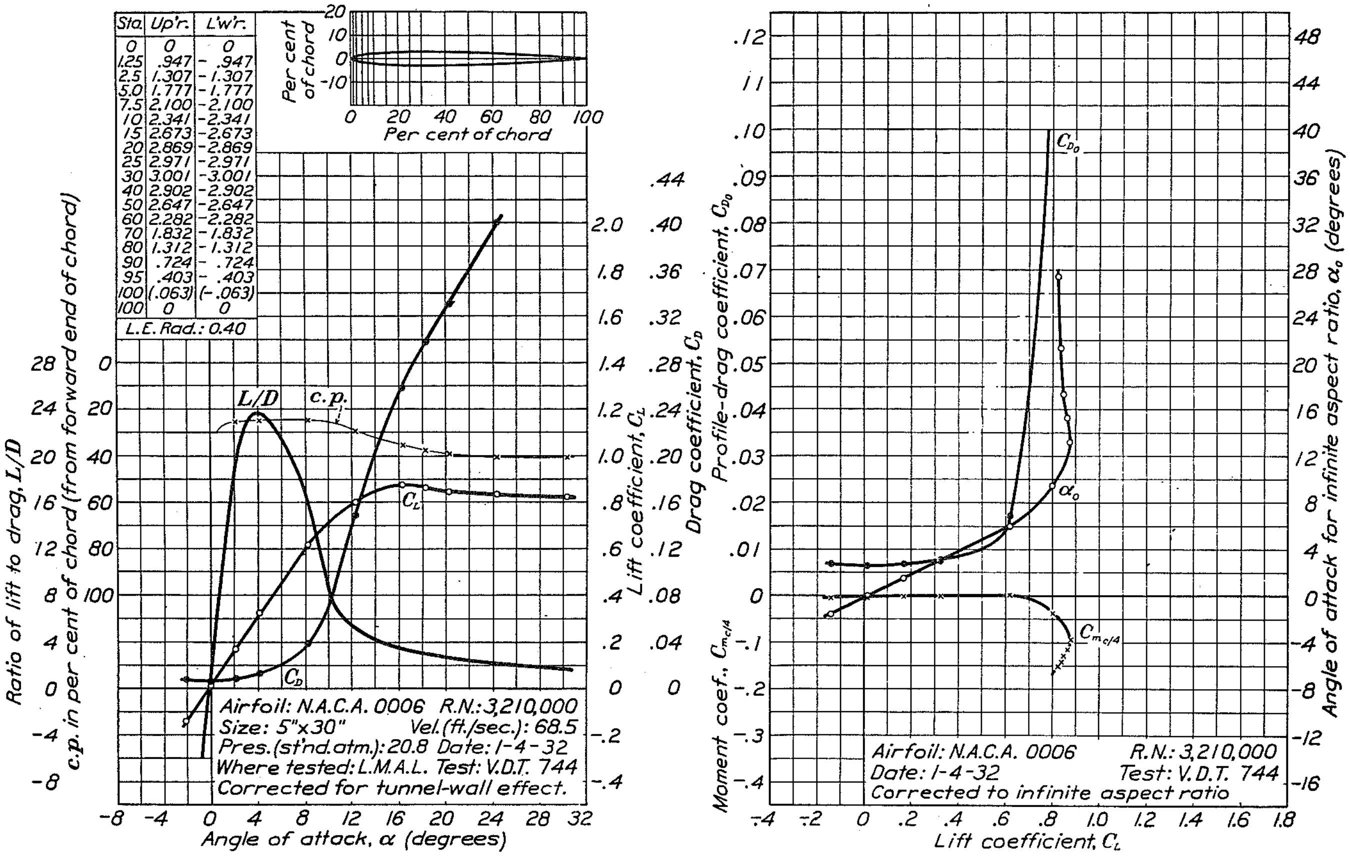
APPARATUS AND METHODS

A description of the variable-density wind tunnel and the method of testing is given in reference 8. The models, which are made of duralumin, have a chord of 5 inches and a span of 30 inches. They were constructed from the computed ordinates by the method described in reference 8.

Routine measurements of lift, drag, and pitching moment about a point on the chord one quarter of the chord behind its forward end were made at a Reynolds Number of approximately 3,000,000 (tank pressure, approximately 20 atmospheres). Groups of airfoils were first tested to study the variations with thickness, each group containing airfoils of different thicknesses but having the same mean line. Finally, all airfoils having a thickness of 12 percent of the chord were tested to study the variations with changes in the mean line.

RESULTS

The results are presented in the standard graphic form (figs. 4 to 80) as coefficients corrected after the method of reference 8 to give airfoil characteristics for infinite aspect ratio and aspect ratio 6. Where more than one test has been used for the analysis, the infinite aspect ratio characteristics from the earlier test have been indicated by additional points on the figure. Table I gives the important characteristics of all the airfoils.



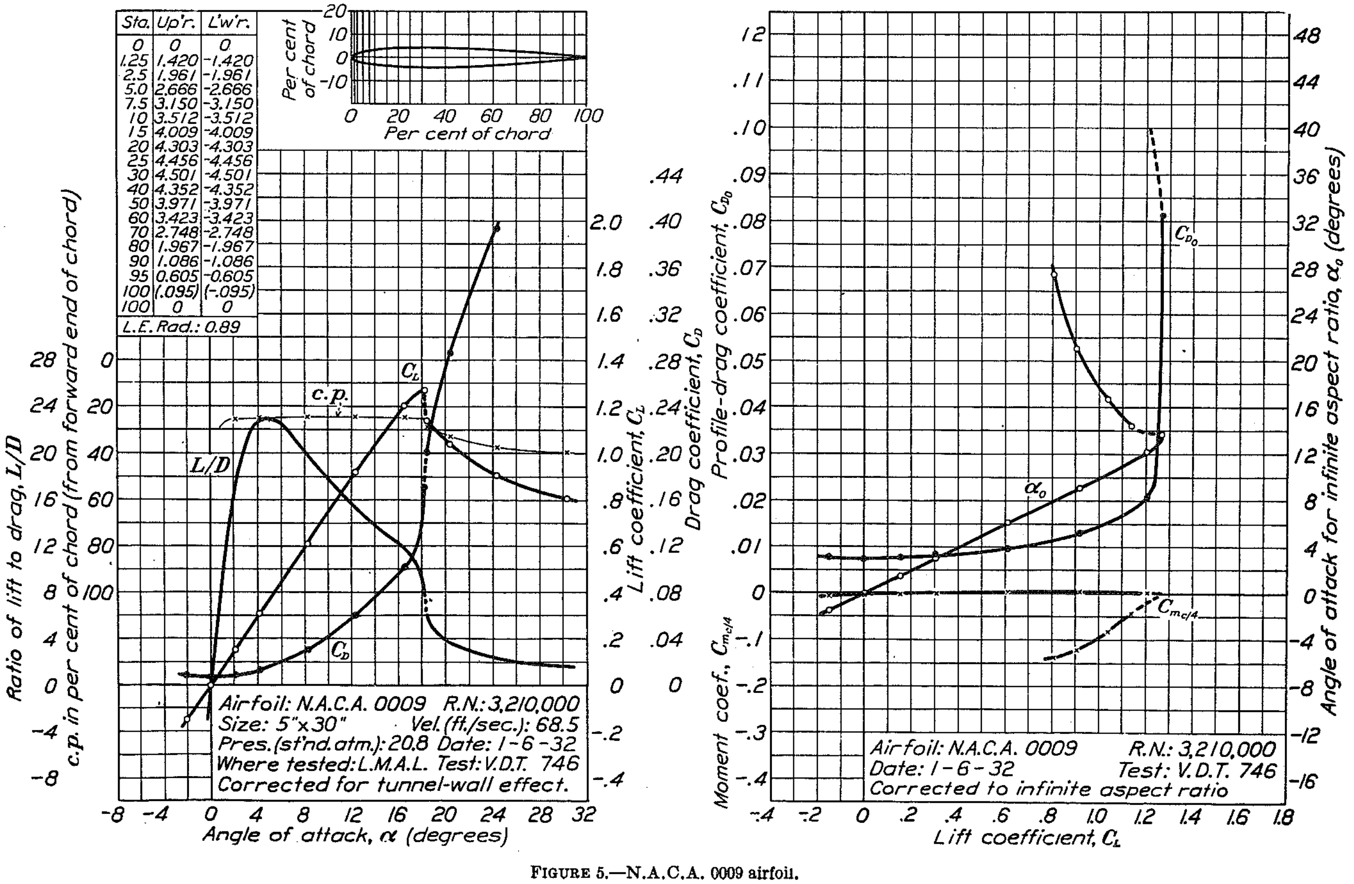
Sta.	Up'r.	L'w'r.
0	0	0
1.25	.947	- .947
2.5	1.307	-1.307
5.0	1.777	-1.777
7.5	2.100	-2.100
10	2.341	-2.341
15	2.673	-2.673
20	2.869	-2.869
25	2.971	-2.971
30	3.001	-3.001
40	2.902	-2.902
50	2.647	-2.647
60	2.282	-2.282
70	1.832	-1.832
80	1.312	-1.312
90	.724	- .724
95	.403	- .403
100	(.063)	(- .063)
100	0	0

L.E. Rad.: 0.40

Airfoil: N.A.C.A. 0006 R.N.: 3,210,000
Size: 5"x30" Vel. (ft./sec.): 68.5
Pres. (st'nd. atm.): 20.8 Date: 1-4-32
Where tested: L.M.A.L. Test: V.D.T. 744
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 0006 R.N.: 3,210,000
Date: 1-4-32 Test: V.D.T. 744
Corrected to infinite aspect ratio

FIGURE 4.—N.A.C.A. 0006 airfoil.



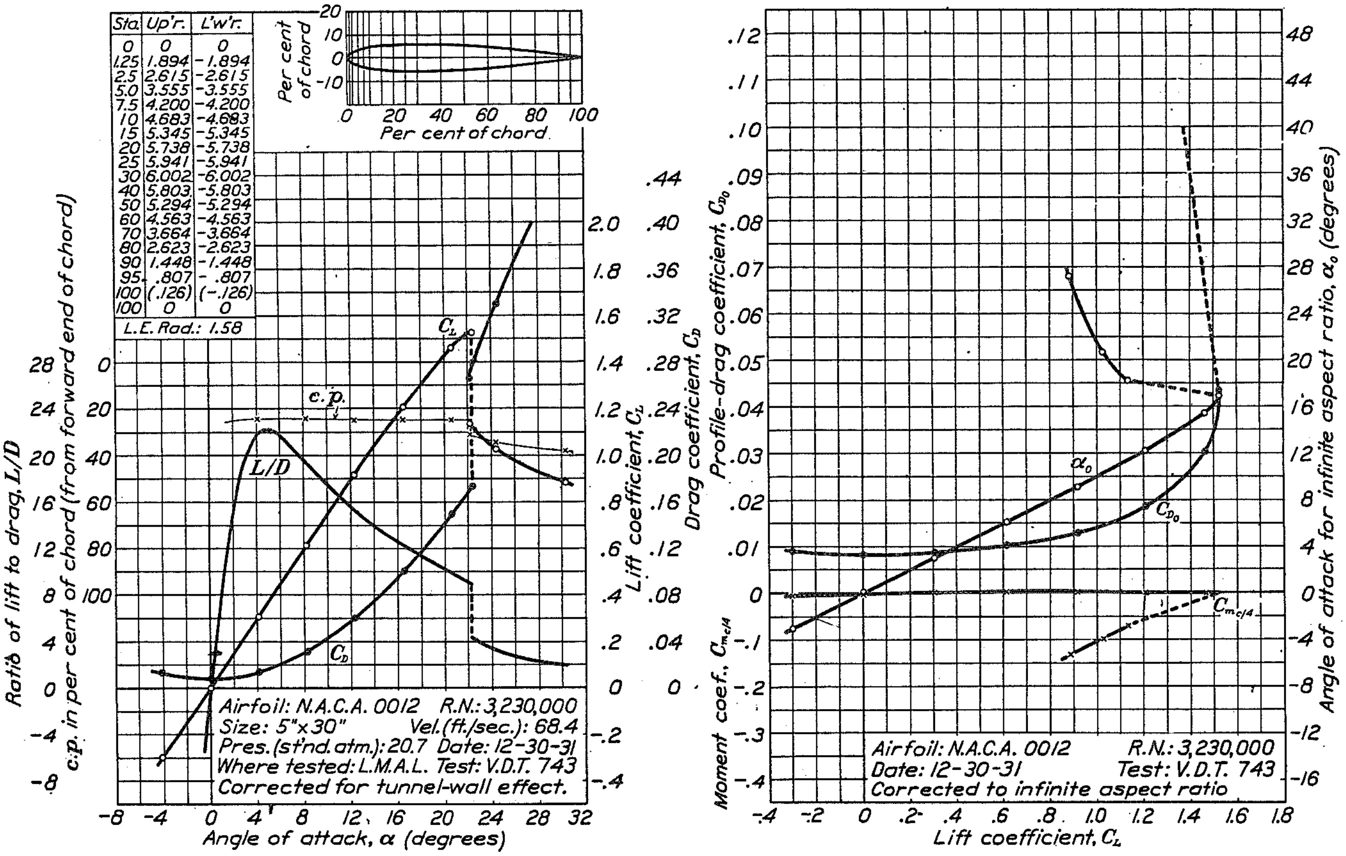
Sta.	Up'r.	L'w'r.
0	0	0
1.25	1.420	-1.420
2.5	1.961	-1.961
5.0	2.666	-2.666
7.5	3.150	-3.150
10	3.512	-3.512
15	4.009	-4.009
20	4.303	-4.303
25	4.456	-4.456
30	4.501	-4.501
40	4.352	-4.352
50	3.971	-3.971
60	3.423	-3.423
70	2.748	-2.748
80	1.967	-1.967
90	1.086	-1.086
95	0.605	-0.605
100	(.095)	(-.095)
100	0	0

L.E. Rad.: 0.89

Airfoil: N.A.C.A. 0009 R.N.: 3,210,000
Size: 5"x30" Vel. (ft./sec.): 68.5
Pres. (st'nd. atm.): 20.8 Date: 1-6-32
Where tested: L.M.A.L. Test: V.D.T. 746
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 0009 R.N.: 3,210,000
Date: 1-6-32 Test: V.D.T. 746
Corrected to infinite aspect ratio

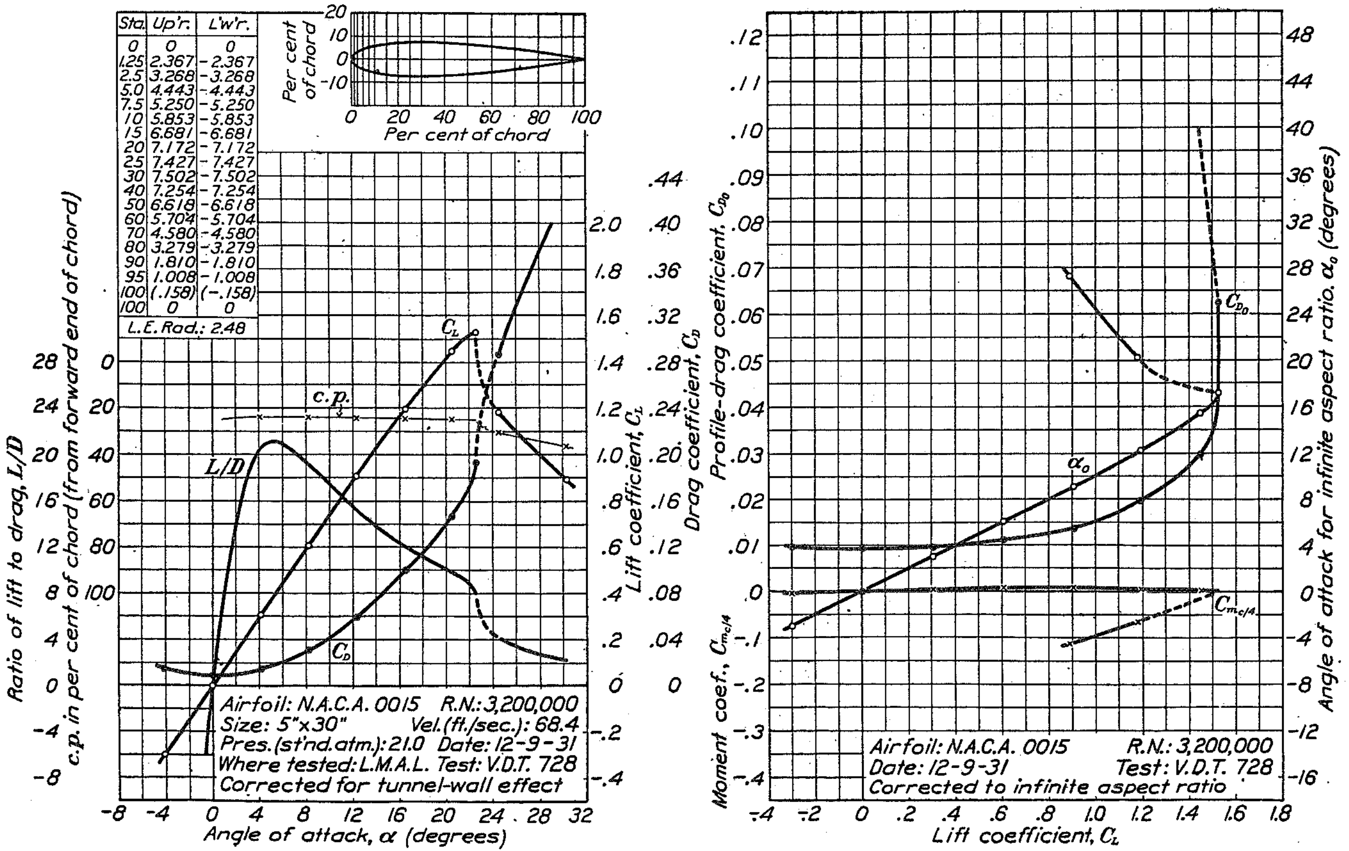
FIGURE 5.—N.A.C.A. 0009 airfoil.



Sta.	Up'r.	L'w'r.
0	0	0
1.25	1.894	-1.894
2.5	2.615	-2.615
5.0	3.555	-3.555
7.5	4.200	-4.200
10	4.683	-4.683
15	5.345	-5.345
20	5.738	-5.738
25	5.941	-5.941
30	6.002	-6.002
40	5.803	-5.803
50	5.294	-5.294
60	4.563	-4.563
70	3.664	-3.664
80	2.623	-2.623
90	1.448	-1.448
95	.807	-.807
100	(.126)	(-.126)
100	0	0

L.E. Rad.: 1.58

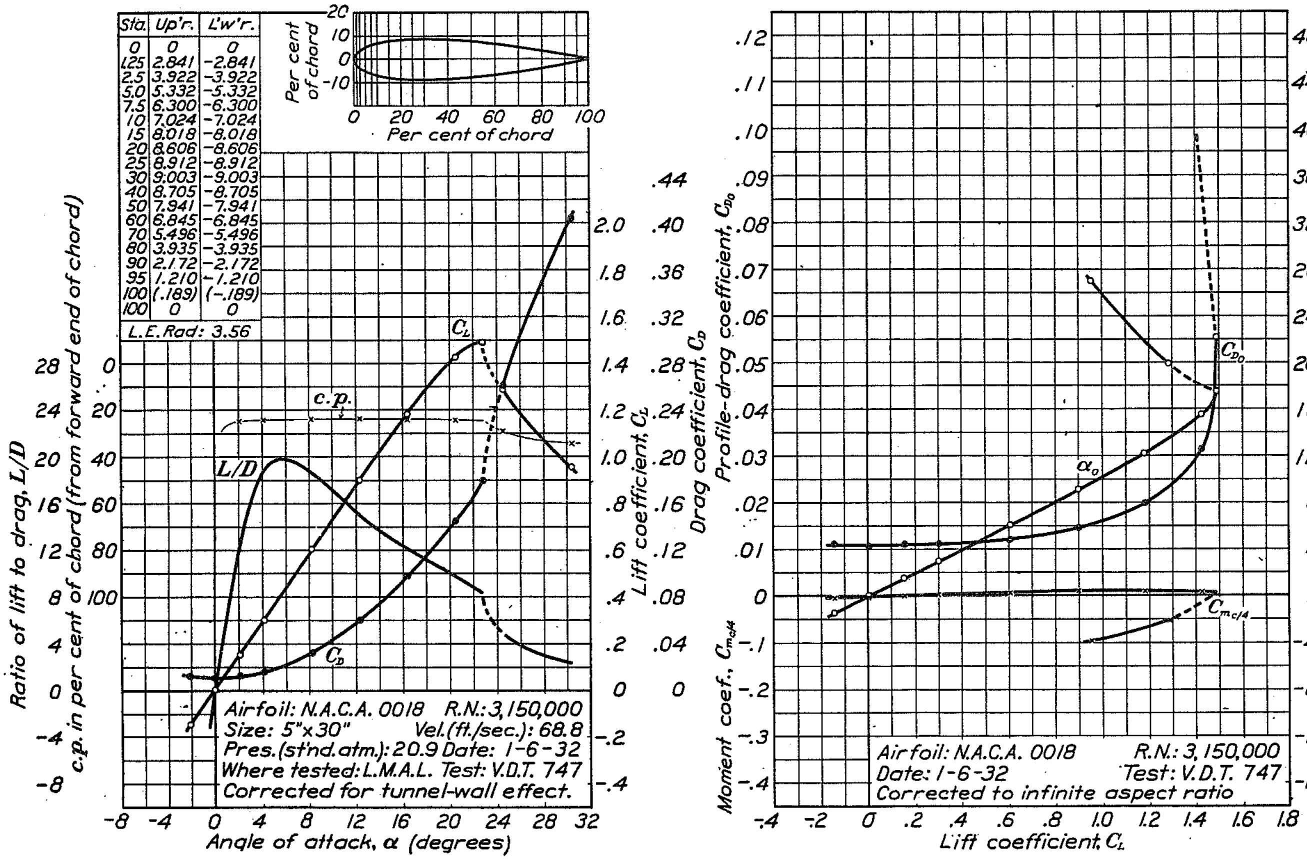
FIGURE 6.—N.A.C.A. 0012 airfoil.



Sta.	Up'r.	L'w'r.
0	0	0
1.25	2.367	-2.367
2.5	3.268	-3.268
5.0	4.443	-4.443
7.5	5.250	-5.250
10	5.853	-5.853
15	6.681	-6.681
20	7.172	-7.172
25	7.427	-7.427
30	7.502	-7.502
40	7.254	-7.254
50	6.618	-6.618
60	5.704	-5.704
70	4.580	-4.580
80	3.279	-3.279
90	1.810	-1.810
95	1.008	-1.008
100	(.158)	(-.158)
100	0	0

L.E. Rad.: 2.48

FIGURE 7.—N.A.C.A. 0015 airfoil.



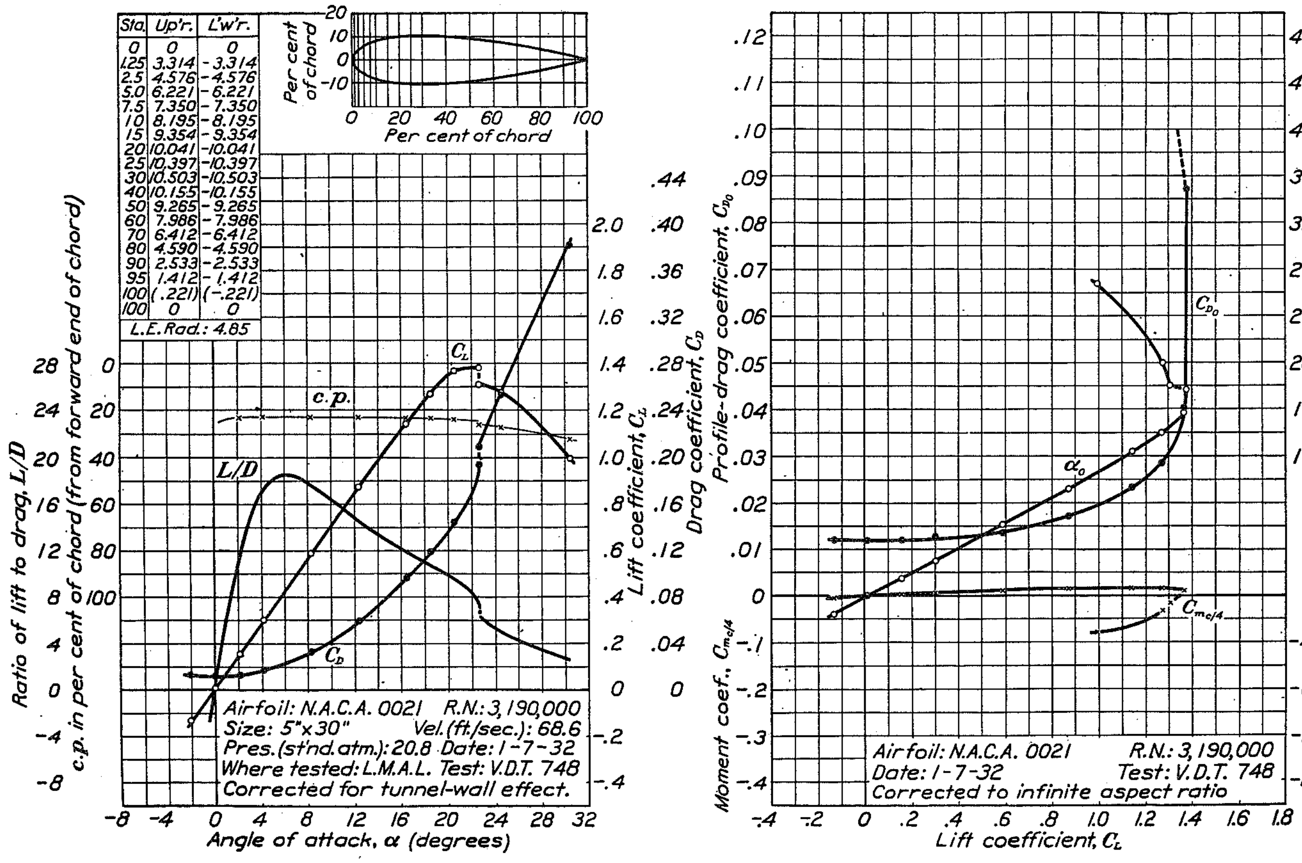
Sta.	Up'r.	L'w'r.
0	0	0
1.25	2.841	-2.841
2.5	3.922	-3.922
5.0	5.332	-5.332
7.5	6.300	-6.300
10	7.024	-7.024
15	8.018	-8.018
20	8.606	-8.606
25	8.912	-8.912
30	9.003	-9.003
40	8.705	-8.705
50	7.941	-7.941
60	6.845	-6.845
70	5.496	-5.496
80	3.935	-3.935
90	2.172	-2.172
95	1.210	-1.210
100	(.189)	(-.189)
100	0	0

L.E. Rad.: 3.56

Airfoil: N.A.C.A. 0018 R.N.: 3,150,000
Size: 5"×30" Vel. (ft./sec.): 68.8
Pres. (st'nd. atm.): 20.9 Date: 1-6-32
Where tested: L.M.A.L. Test: V.D.T. 747
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 0018 R.N.: 3,150,000
Date: 1-6-32 Test: V.D.T. 747
Corrected to infinite aspect ratio

FIGURE 8.—N.A.C.A. 0018 airfoil.



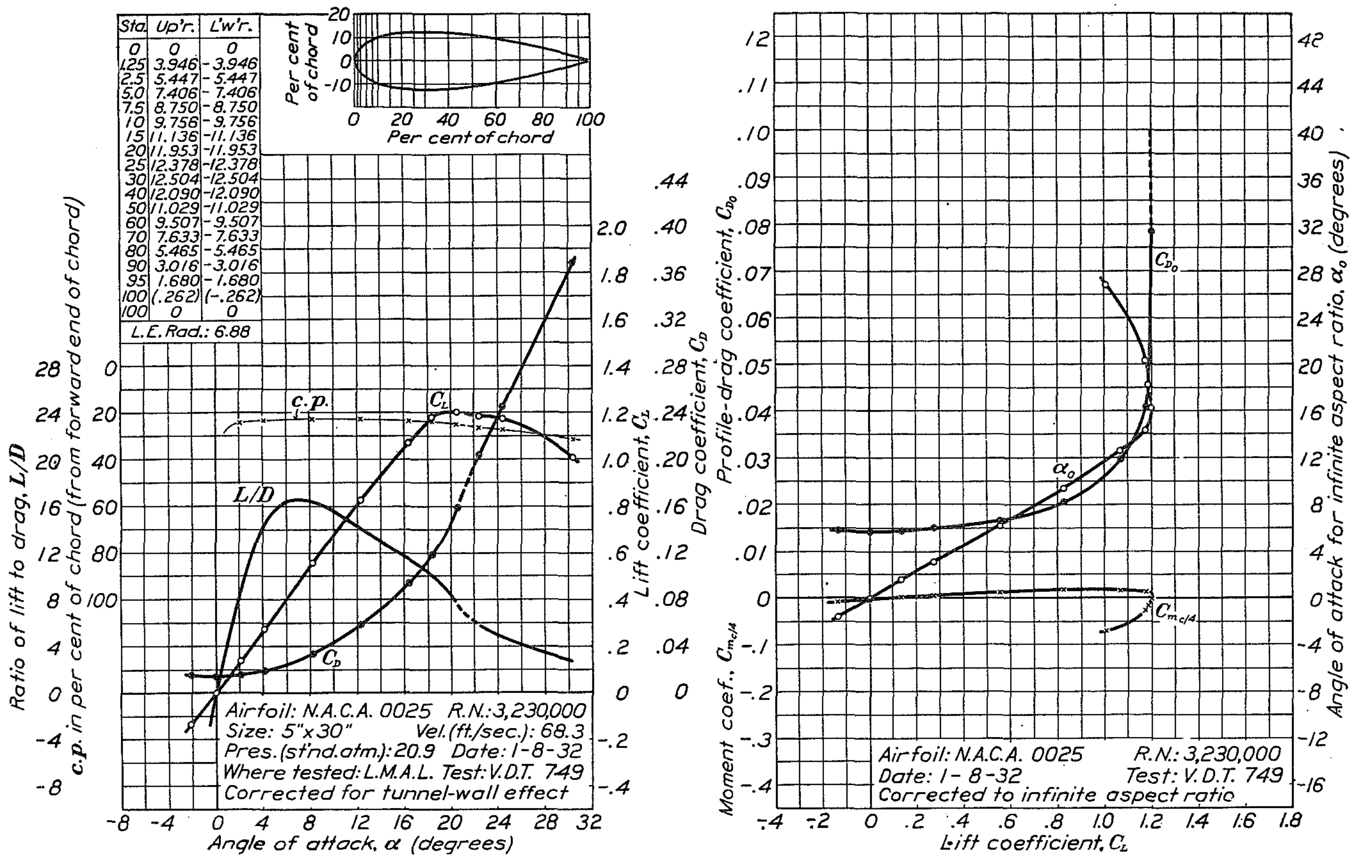
Sta.	Up'r.	L'w'r.
0	0	0
1.25	3.314	-3.314
2.5	4.576	-4.576
5.0	6.221	-6.221
7.5	7.350	-7.350
10	8.195	-8.195
15	9.354	-9.354
20	10.041	-10.041
25	10.397	-10.397
30	10.503	-10.503
40	10.155	-10.155
50	9.265	-9.265
60	7.986	-7.986
70	6.412	-6.412
80	4.590	-4.590
90	2.533	-2.533
95	1.412	-1.412
100	(.221)	(-.221)
100	0	0

L.E. Rad.: 4.85

Airfoil: N.A.C.A. 0021 R.N.: 3,190,000
Size: 5"×30" Vel. (ft./sec.): 68.6
Pres. (st'nd. atm.): 20.8 Date: 1-7-32
Where tested: L.M.A.L. Test: V.D.T. 748
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 0021 R.N.: 3,190,000
Date: 1-7-32 Test: V.D.T. 748
Corrected to infinite aspect ratio

FIGURE 9.—N.A.C.A. 0021 airfoil.



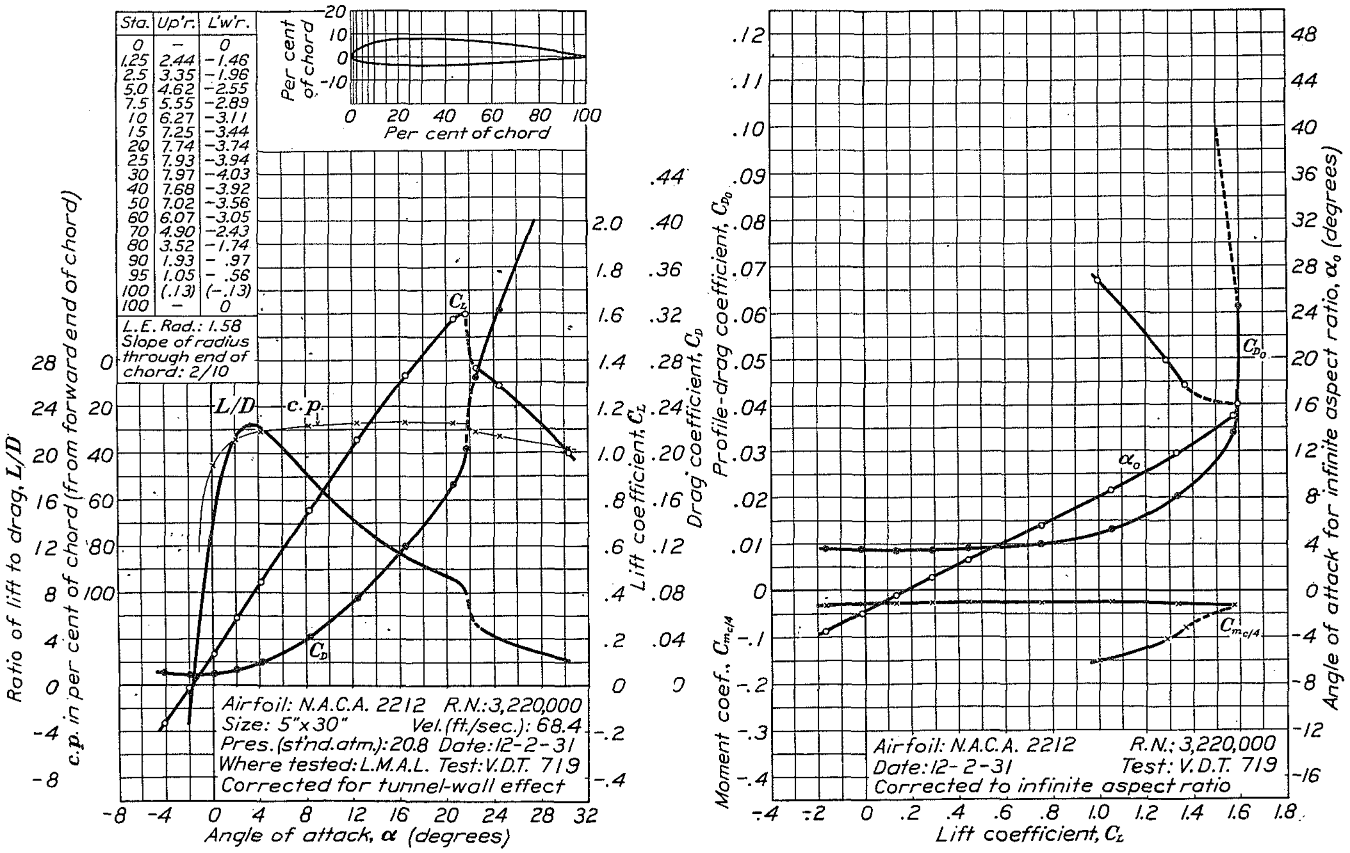
Sta.	Up'r.	L'w'r.
0	0	0
1.25	3.946	-3.946
2.5	5.447	-5.447
5.0	7.406	-7.406
7.5	8.750	-8.750
10	9.756	-9.756
15	11.136	-11.136
20	11.953	-11.953
25	12.378	-12.378
30	12.504	-12.504
40	12.090	-12.090
50	11.029	-11.029
60	9.507	-9.507
70	7.633	-7.633
80	5.465	-5.465
90	3.016	-3.016
95	1.680	-1.680
100	(.262)	(-.262)
100	0	0

L.E. Rad.: 6.88

Airfoil: N.A.C.A. 0025 R.N.: 3,230,000
Size: 5"x30" Vel. (ft./sec.): 68.3
Pres. (st'nd. atm.): 20.9 Date: 1-8-32
Where tested: L.M.A.L. Test: V.D.T. 749
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 0025 R.N.: 3,230,000
Date: 1-8-32 Test: V.D.T. 749
Corrected to infinite aspect ratio

FIGURE 10.—N.A.C.A. 0025 airfoil.



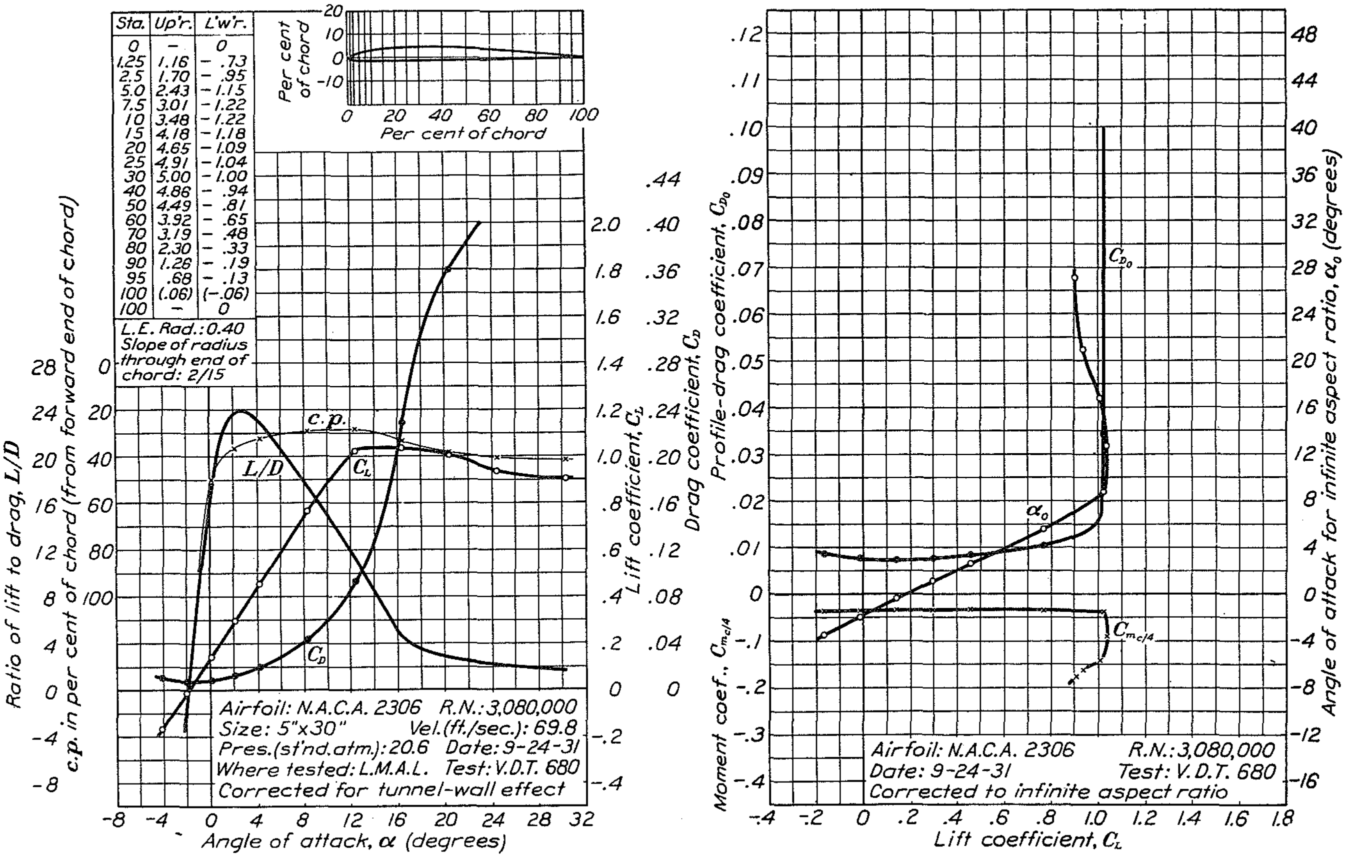
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.44	-1.46
2.5	3.35	-1.96
5.0	4.62	-2.55
7.5	5.55	-2.89
10	6.27	-3.11
15	7.25	-3.44
20	7.74	-3.74
25	7.93	-3.94
30	7.97	-4.03
40	7.68	-3.92
50	7.02	-3.56
60	6.07	-3.05
70	4.90	-2.43
80	3.52	-1.74
90	1.93	- .97
95	1.05	- .56
100	(.13)	(-.13)
100	–	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 2/10

Airfoil: N.A.C.A. 2212 R.N.: 3,220,000
Size: 5"x30" Vel. (ft./sec.): 68.4
Pres. (st'nd. atm.): 20.8 Date: 12-2-31
Where tested: L.M.A.L. Test: V.D.T. 719
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2212 R.N.: 3,220,000
Date: 12-2-31 Test: V.D.T. 719
Corrected to infinite aspect ratio

FIGURE 11.—N.A.C.A. 2212 airfoil.



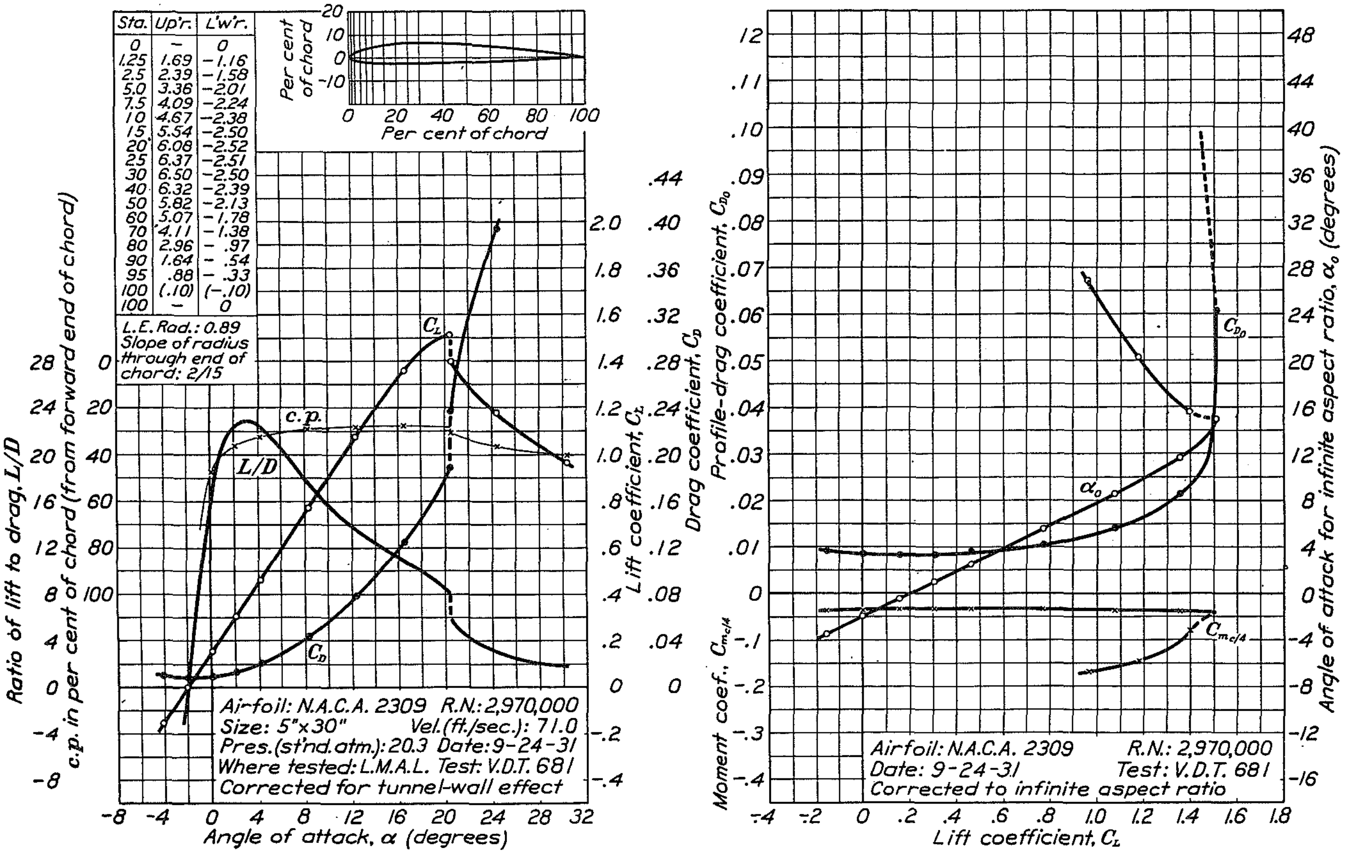
Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.16	– .73
2.5	1.70	– .95
5.0	2.43	–1.15
7.5	3.01	–1.22
10	3.48	–1.22
15	4.18	–1.18
20	4.65	–1.09
25	4.91	–1.04
30	5.00	–1.00
40	4.86	– .94
50	4.49	– .81
60	3.92	– .65
70	3.19	– .48
80	2.30	– .33
90	1.26	– .19
95	.68	– .13
100	(.06)	(–.06)
100	–	0

L.E. Rad.: 0.40
Slope of radius through end of chord: 2/15

Airfoil: N.A.C.A. 2306 R.N.: 3,080,000
Size: 5"x30" Vel. (ft./sec.): 69.8
Pres. (st'nd. atm.): 20.6 Date: 9-24-31
Where tested: L.M.A.L. Test: V.D.T. 680
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2306 R.N.: 3,080,000
Date: 9-24-31 Test: V.D.T. 680
Corrected to infinite aspect ratio

FIGURE 12.—N.A.C.A. 2306 airfoil.



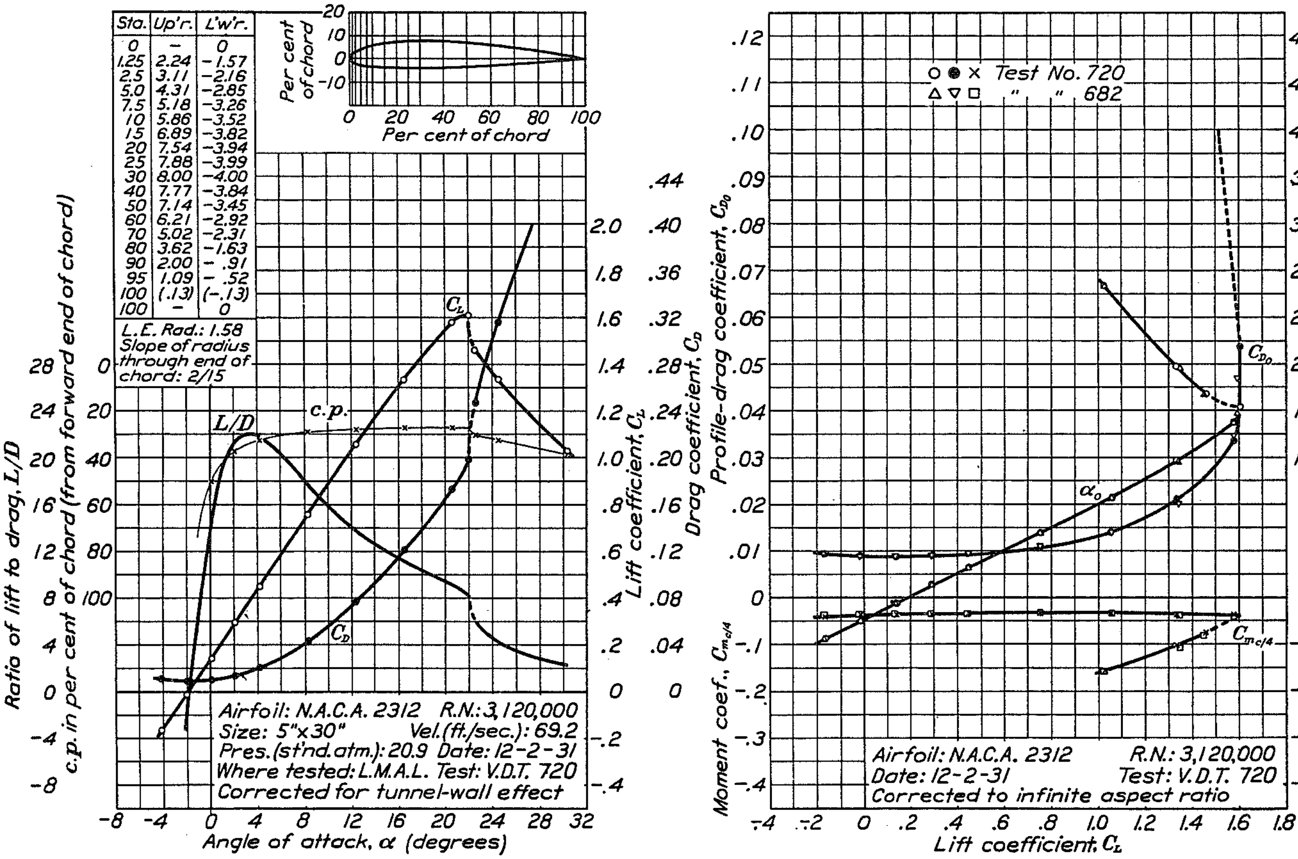
Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.69	–1.16
2.5	2.39	–1.58
5.0	3.36	–2.01
7.5	4.09	–2.24
10	4.67	–2.38
15	5.54	–2.50
20	6.08	–2.52
25	6.37	–2.51
30	6.50	–2.50
40	6.32	–2.39
50	5.82	–2.13
60	5.07	–1.78
70	4.11	–1.38
80	2.96	– .97
90	1.64	– .54
95	.88	– .33
100	(.10)	(–.10)
100	–	0

L.E. Rad.: 0.89
Slope of radius through end of chord: 2/15

Airfoil: N.A.C.A. 2309 R.N.: 2,970,000
Size: 5"x30" Vel. (ft./sec.): 71.0
Pres. (st'nd. atm.): 20.3 Date: 9-24-31
Where tested: L.M.A.L. Test: V.D.T. 681
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2309 R.N.: 2,970,000
Date: 9-24-31 Test: V.D.T. 681
Corrected to infinite aspect ratio

FIGURE 13.—N.A.C.A. 2309 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.24	−1.57
2.5	3.11	−2.16
5.0	4.31	−2.85
7.5	5.18	−3.26
10	5.86	−3.52
15	6.89	−3.82
20	7.54	−3.94
25	7.88	−3.99
30	8.00	−4.00
40	7.77	−3.84
50	7.14	−3.45
60	6.21	−2.92
70	5.02	−2.31
80	3.62	−1.63
90	2.00	−.91
95	1.09	−.52
100	(.13)	(−.13)
100	—	0

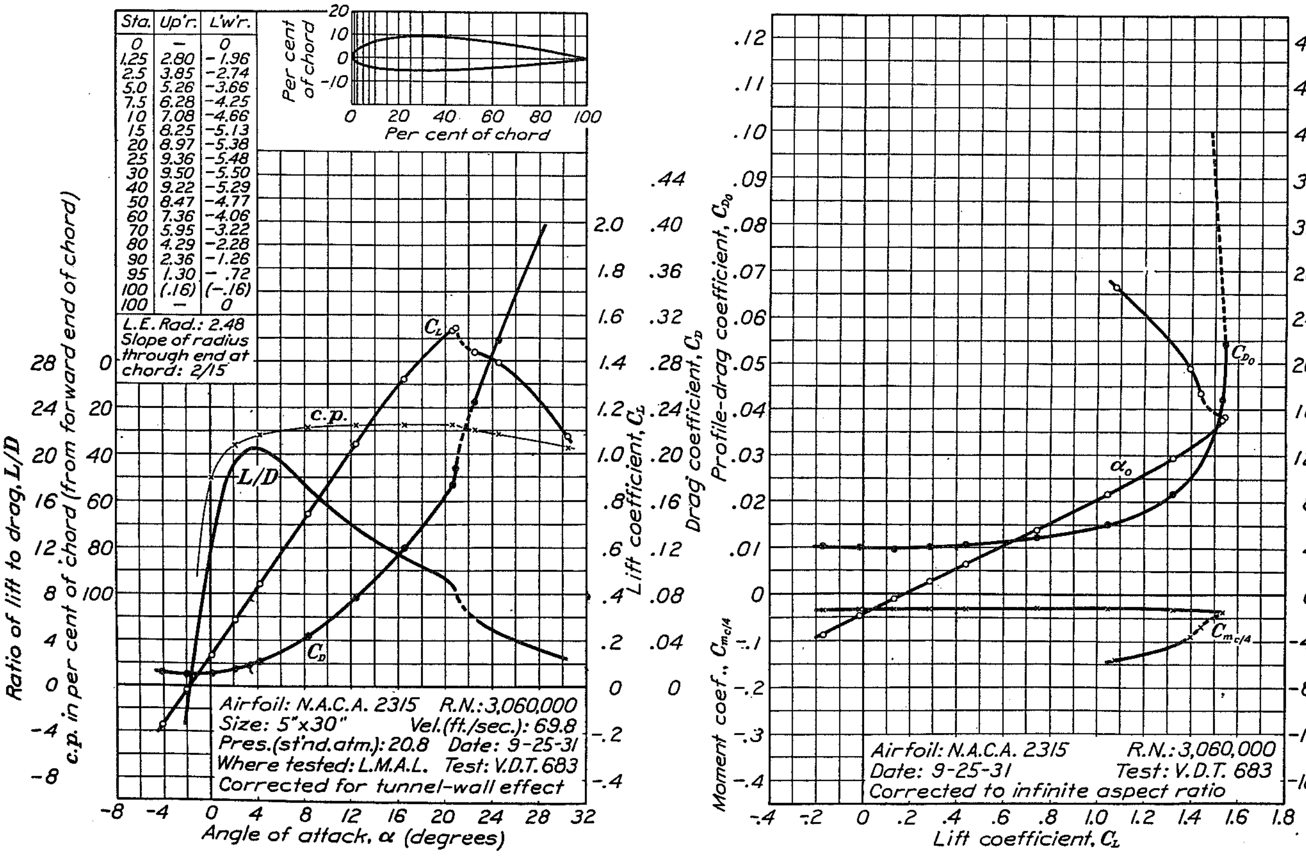
L.E. Rad.: 1.58
Slope of radius through end of chord: 2/15

Airfoil: N.A.C.A. 2312 R.N.: 3,120,000
Size: 5"x30" Vel.(ft./sec.): 69.2
Pres.(st'nd.atm.): 20.9 Date: 12-2-31
Where tested: L.M.A.L. Test: V.D.T. 720
Corrected for tunnel-wall effect

○ ● × Test No. 720
△ ▽ □ " " 682

Airfoil: N.A.C.A. 2312 R.N.: 3,120,000
Date: 12-2-31 Test: V.D.T. 720
Corrected to infinite aspect ratio

FIGURE 14.—N.A.C.A. 2312 airfoil.



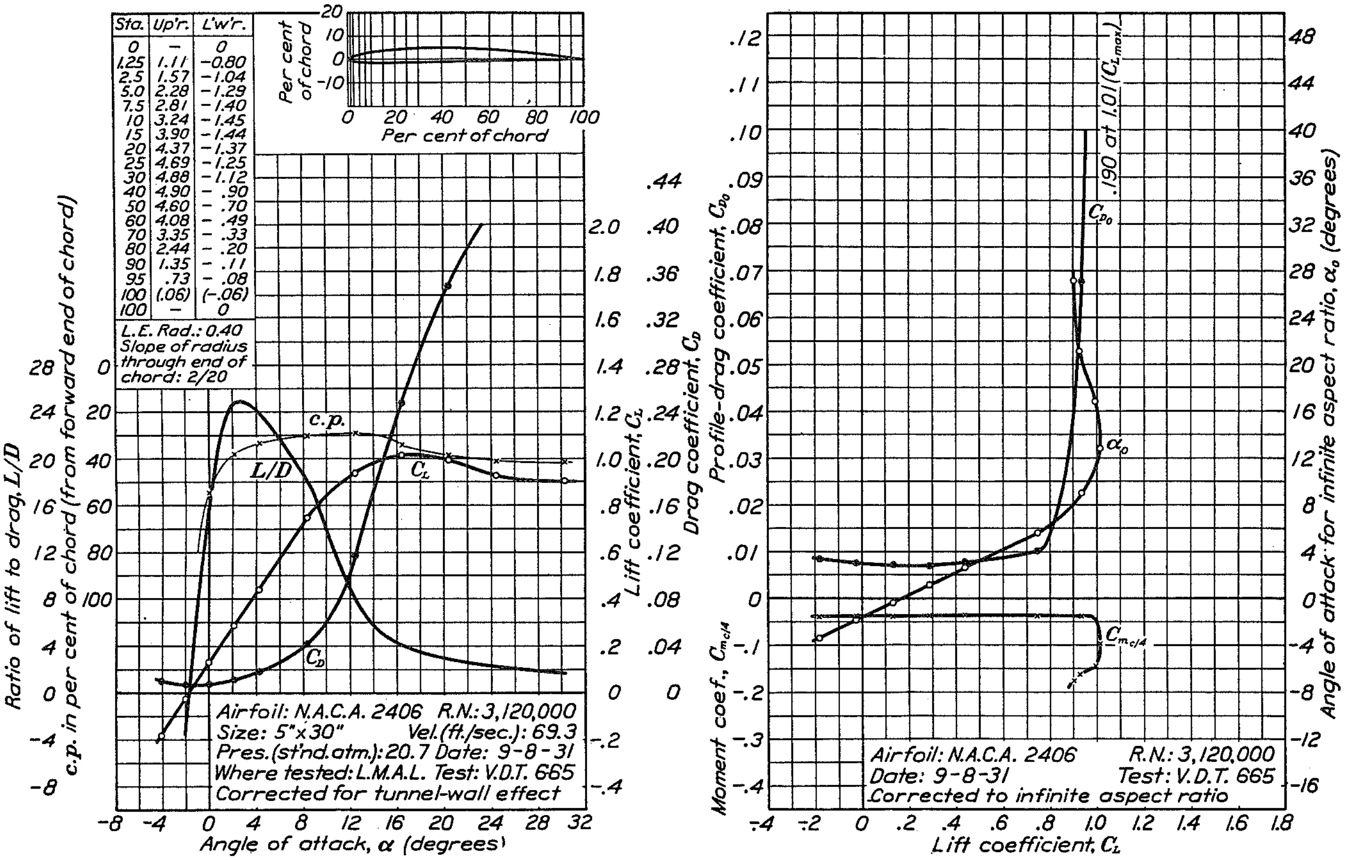
Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.80	−1.96
2.5	3.85	−2.74
5.0	5.26	−3.66
7.5	6.28	−4.25
10	7.08	−4.66
15	8.25	−5.13
20	8.97	−5.38
25	9.36	−5.48
30	9.50	−5.50
40	9.22	−5.29
50	8.47	−4.77
60	7.36	−4.06
70	5.95	−3.22
80	4.29	−2.28
90	2.36	−1.26
95	1.30	−.72
100	(.16)	(−.16)
100	—	0

L.E. Rad.: 2.48
Slope of radius through end at chord: 2/15

Airfoil: N.A.C.A. 2315 R.N.: 3,060,000
Size: 5"x30" Vel.(ft./sec.): 69.8
Pres.(st'nd.atm.): 20.8 Date: 9-25-31
Where tested: L.M.A.L. Test: V.D.T. 683
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2315 R.N.: 3,060,000
Date: 9-25-31 Test: V.D.T. 683
Corrected to infinite aspect ratio

FIGURE 15.—N.A.C.A. 2315 airfoil.



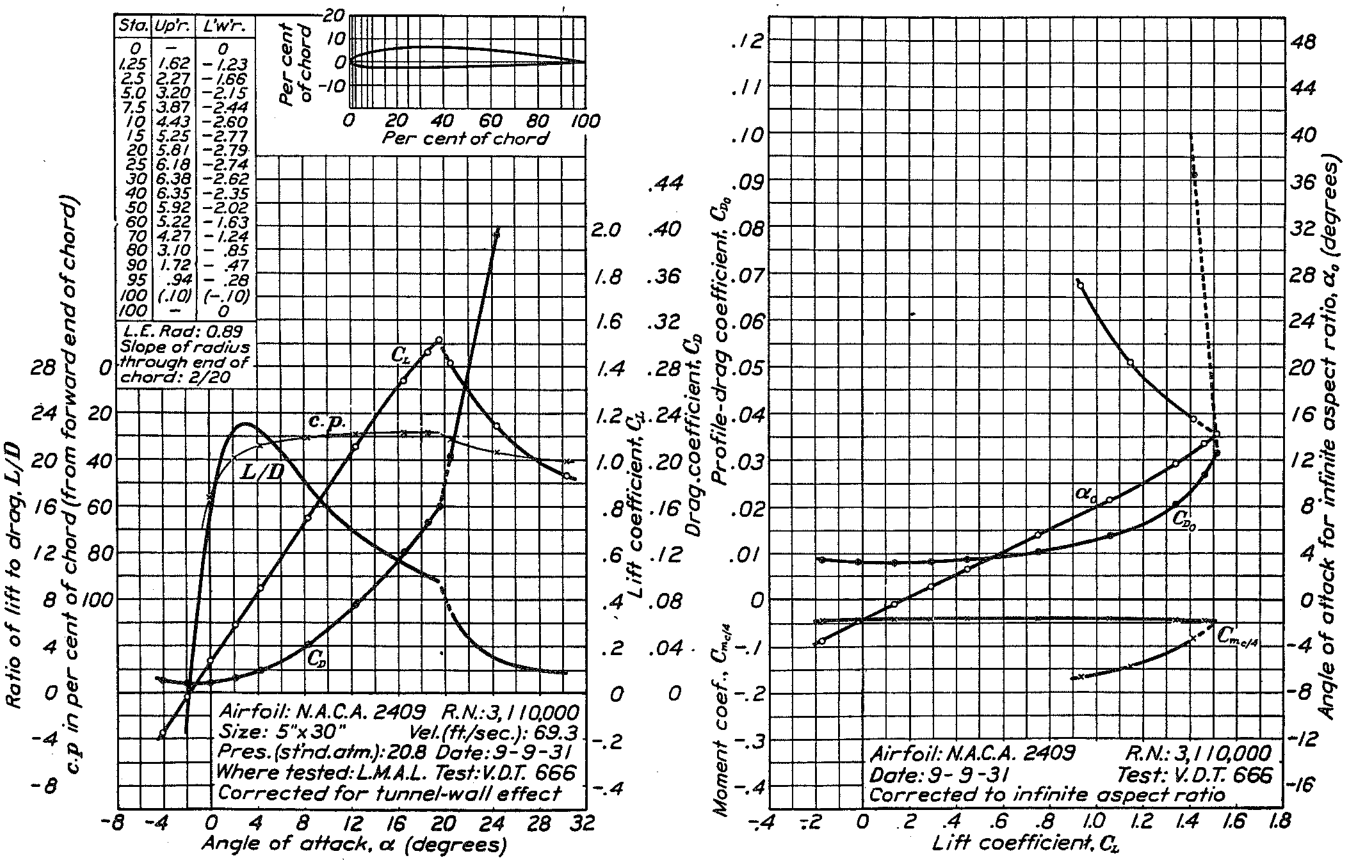
Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.11	-0.80
2.5	1.57	-1.04
5.0	2.28	-1.29
7.5	2.81	-1.40
10	3.24	-1.45
15	3.90	-1.44
20	4.37	-1.37
25	4.69	-1.25
30	4.88	-1.12
40	4.90	- .90
50	4.60	- .70
60	4.08	- .49
70	3.35	- .33
80	2.44	- .20
90	1.35	- .11
95	.73	- .08
100	(.06)	(-.06)
100	—	0

L.E. Rad.: 0.40
Slope of radius through end of chord: 2/20

Airfoil: N.A.C.A. 2406 R.N.: 3,120,000
Size: 5"x30" Vel.(ft./sec.): 69.3
Pres.(st'nd.atm.): 20.7 Date: 9-8-31
Where tested: L.M.A.L. Test: V.D.T. 665
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2406 R.N.: 3,120,000
Date: 9-8-31 Test: V.D.T. 665
Corrected to infinite aspect ratio

FIGURE 16.—N.A.C.A. 2406 airfoil.



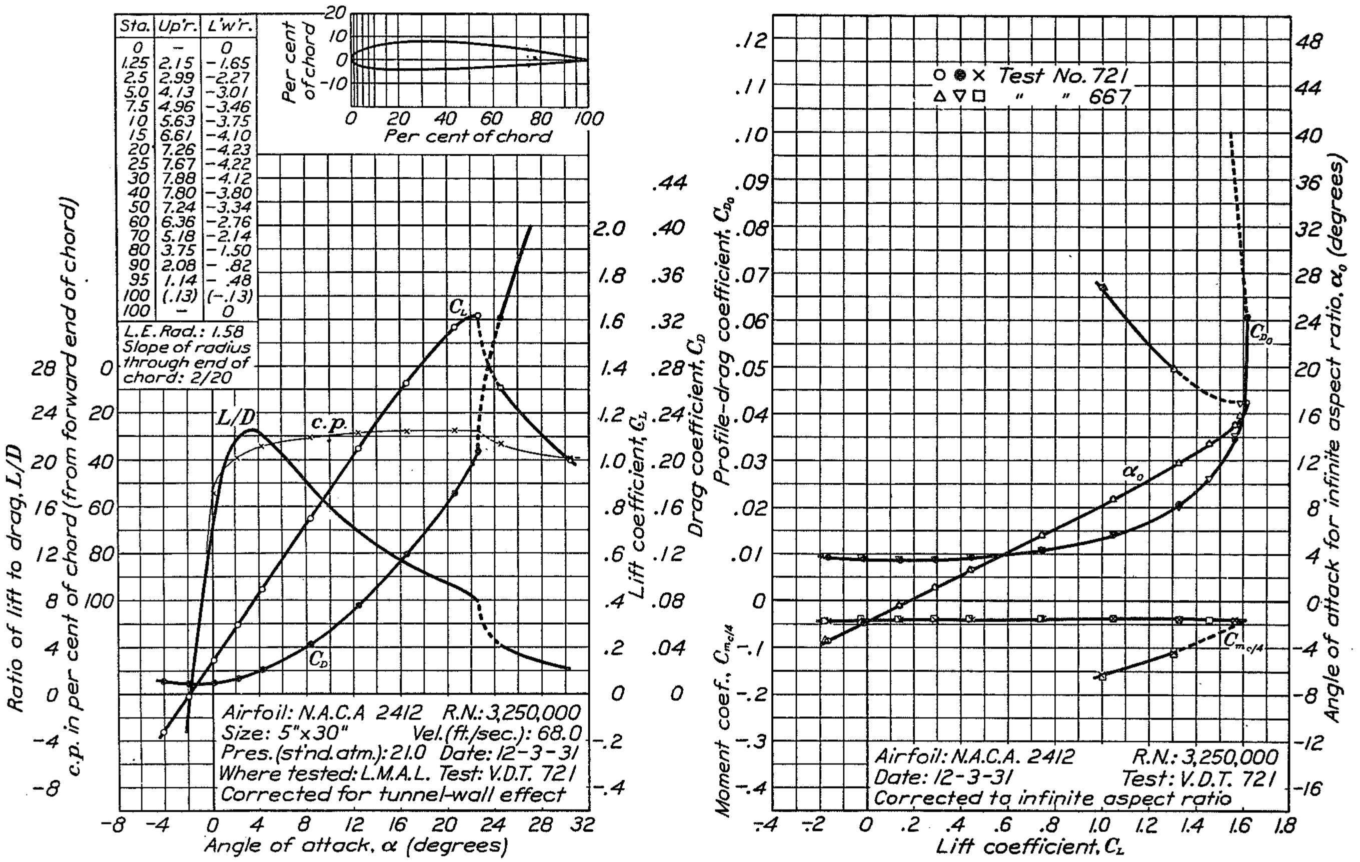
Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.62	-1.23
2.5	2.27	-1.66
5.0	3.20	-2.15
7.5	3.87	-2.44
10	4.43	-2.60
15	5.25	-2.77
20	5.81	-2.79
25	6.18	-2.74
30	6.38	-2.62
40	6.35	-2.35
50	5.92	-2.02
60	5.22	-1.63
70	4.27	-1.24
80	3.10	- .85
90	1.72	- .47
95	.94	- .28
100	(.10)	(-.10)
100	—	0

L.E. Rad: 0.89
Slope of radius through end of chord: 2/20

Airfoil: N.A.C.A. 2409 R.N.: 3,110,000
Size: 5"x30" Vel.(ft./sec.): 69.3
Pres.(st'nd.atm.): 20.8 Date: 9-9-31
Where tested: L.M.A.L. Test: V.D.T. 666
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2409 R.N.: 3,110,000
Date: 9-9-31 Test: V.D.T. 666
Corrected to infinite aspect ratio

FIGURE 17.—N.A.C.A. 2409 airfoil.



Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.15	–1.65
2.5	2.99	–2.27
5.0	4.13	–3.01
7.5	4.96	–3.46
10	5.63	–3.75
15	6.61	–4.10
20	7.26	–4.23
25	7.67	–4.22
30	7.88	–4.12
40	7.80	–3.80
50	7.24	–3.34
60	6.36	–2.76
70	5.18	–2.14
80	3.75	–1.50
90	2.08	– .82
95	1.14	– .48
100	(.13)	(–.13)
100	–	0

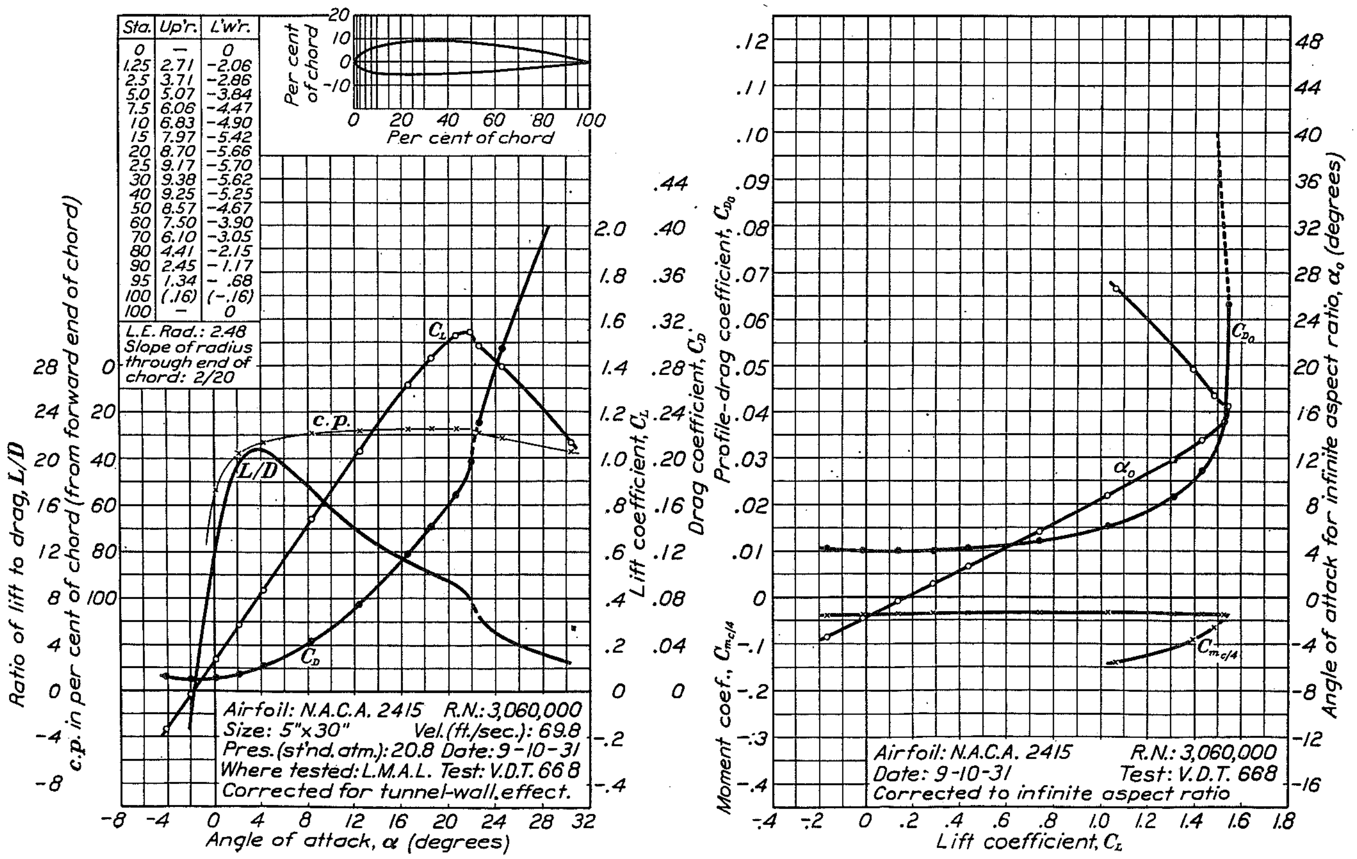
L.E. Rad.: 1.58
Slope of radius through end of chord: 2/20

Airfoil: N.A.C.A 2412 R.N.: 3,250,000
Size: 5"x30" Vel. (ft./sec.): 68.0
Pres. (st'nd. atm.): 21.0 Date: 12-3-31
Where tested: L.M.A.L. Test: V.D.T. 721
Corrected for tunnel-wall effect

○ ● × Test No. 721
△ ▽ □ " " 667

Airfoil: N.A.C.A. 2412 R.N.: 3,250,000
Date: 12-3-31 Test: V.D.T. 721
Corrected to infinite aspect ratio

FIGURE 18.—N.A.C.A. 2412 airfoil.



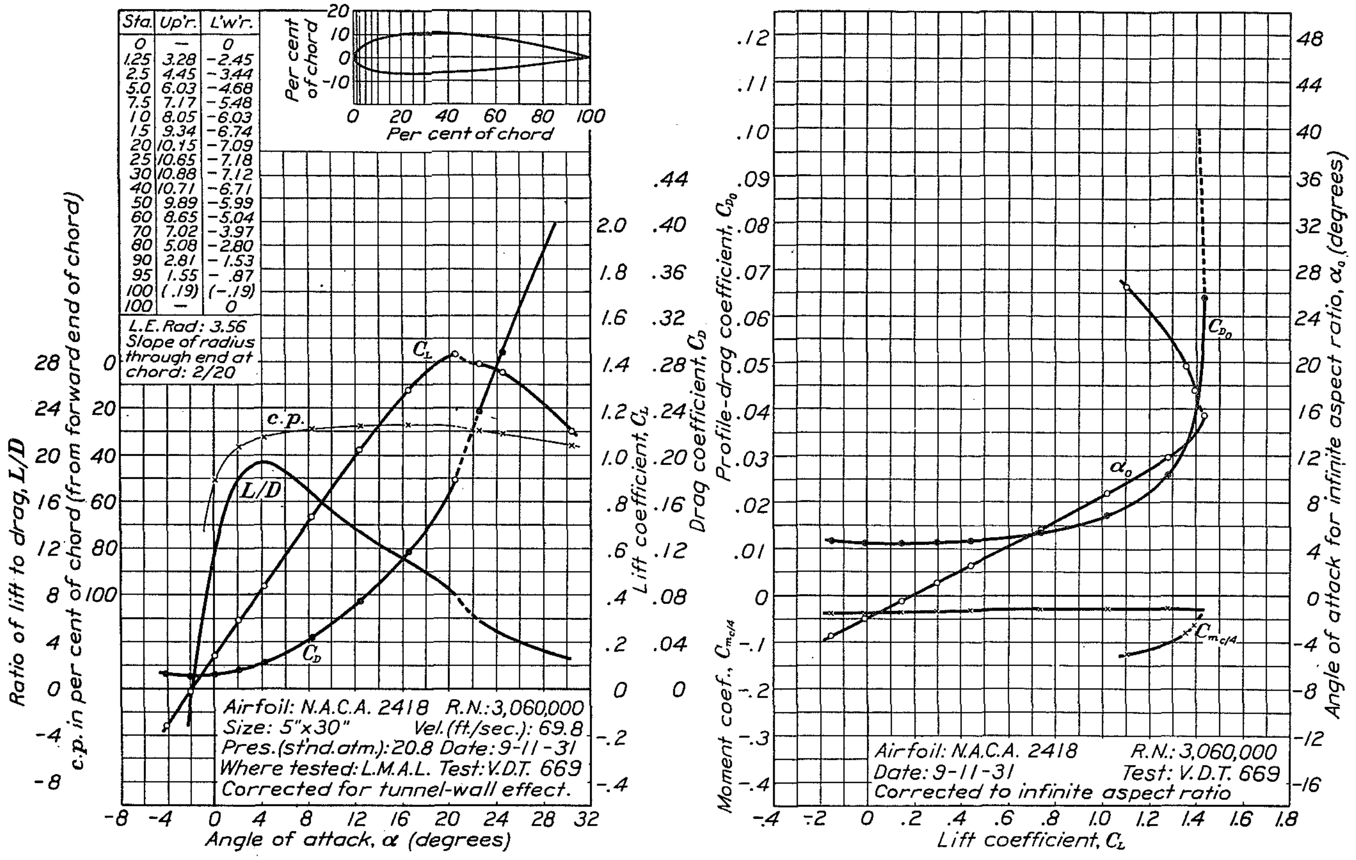
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.71	–2.06
2.5	3.71	–2.86
5.0	5.07	–3.84
7.5	6.06	–4.47
10	6.83	–4.90
15	7.97	–5.42
20	8.70	–5.66
25	9.17	–5.70
30	9.38	–5.62
40	9.25	–5.25
50	8.57	–4.67
60	7.50	–3.90
70	6.10	–3.05
80	4.41	–2.15
90	2.45	–1.17
95	1.34	– .68
100	(.16)	(–.16)
100	–	0

L.E. Rad.: 2.48
Slope of radius through end of chord: 2/20

Airfoil: N.A.C.A. 2415 R.N.: 3,060,000
Size: 5"x30" Vel. (ft./sec.): 69.8
Pres. (st'nd. atm.): 20.8 Date: 9-10-31
Where tested: L.M.A.L. Test: V.D.T. 668
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 2415 R.N.: 3,060,000
Date: 9-10-31 Test: V.D.T. 668
Corrected to infinite aspect ratio

FIGURE 19.—N.A.C.A. 2415 airfoil.



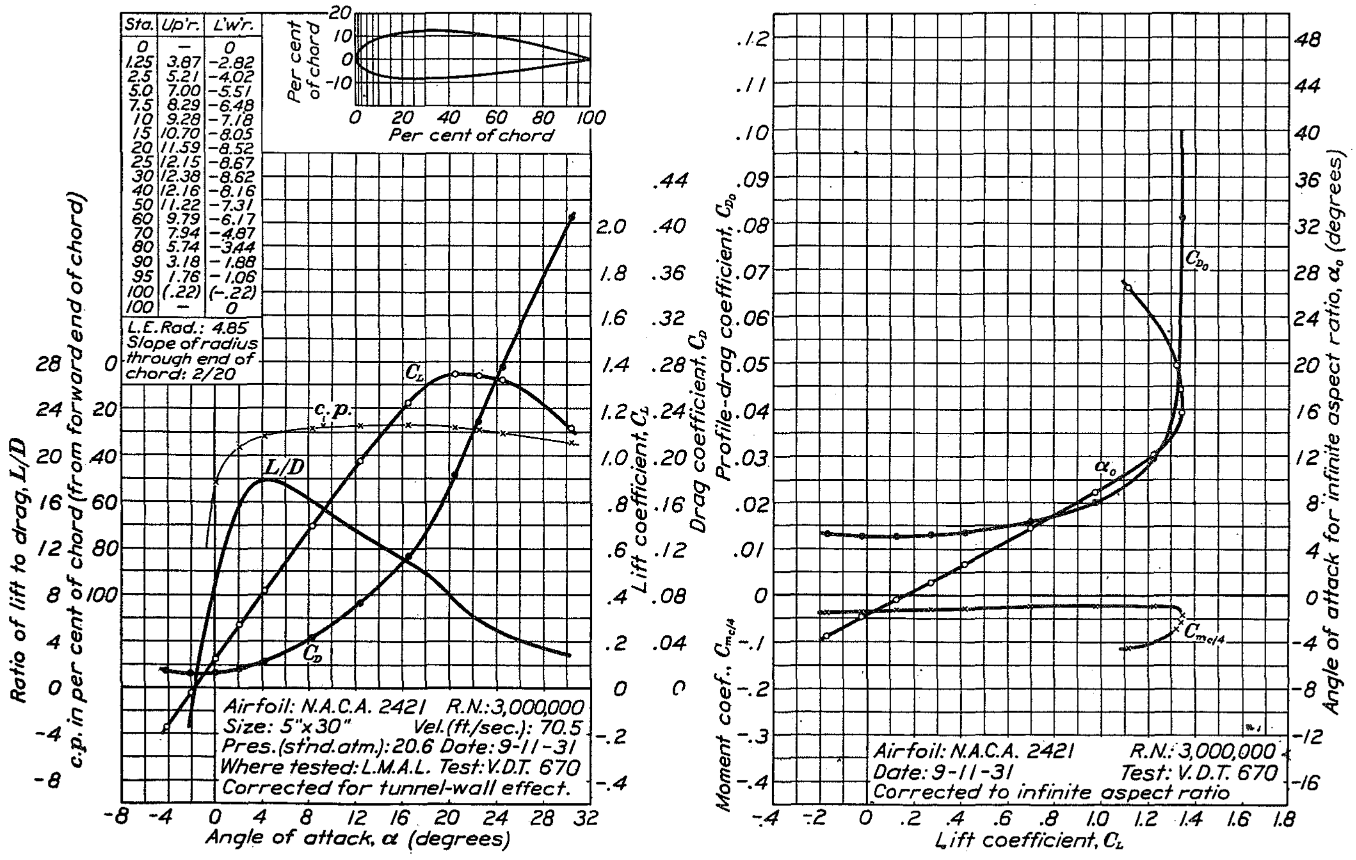
Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.28	-2.45
2.5	4.45	-3.44
5.0	6.03	-4.68
7.5	7.17	-5.48
10	8.05	-6.03
15	9.34	-6.74
20	10.15	-7.09
25	10.65	-7.18
30	10.88	-7.12
40	10.71	-6.71
50	9.89	-5.99
60	8.65	-5.04
70	7.02	-3.97
80	5.08	-2.80
90	2.81	-1.53
95	1.55	- .87
100	(.19)	(-.19)
100	—	0

L.E. Rad: 3.56
Slope of radius through end at chord: 2/20

Airfoil: N.A.C.A. 2418 R.N.: 3,060,000
Size: 5"x30" Vel.(ft./sec.): 69.8
Pres.(st'nd.atm.): 20.8 Date: 9-11-31
Where tested: L.M.A.L. Test: V.D.T. 669
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 2418 R.N.: 3,060,000
Date: 9-11-31 Test: V.D.T. 669
Corrected to infinite aspect ratio

FIGURE 20.—N.A.C.A. 2418 airfoil.



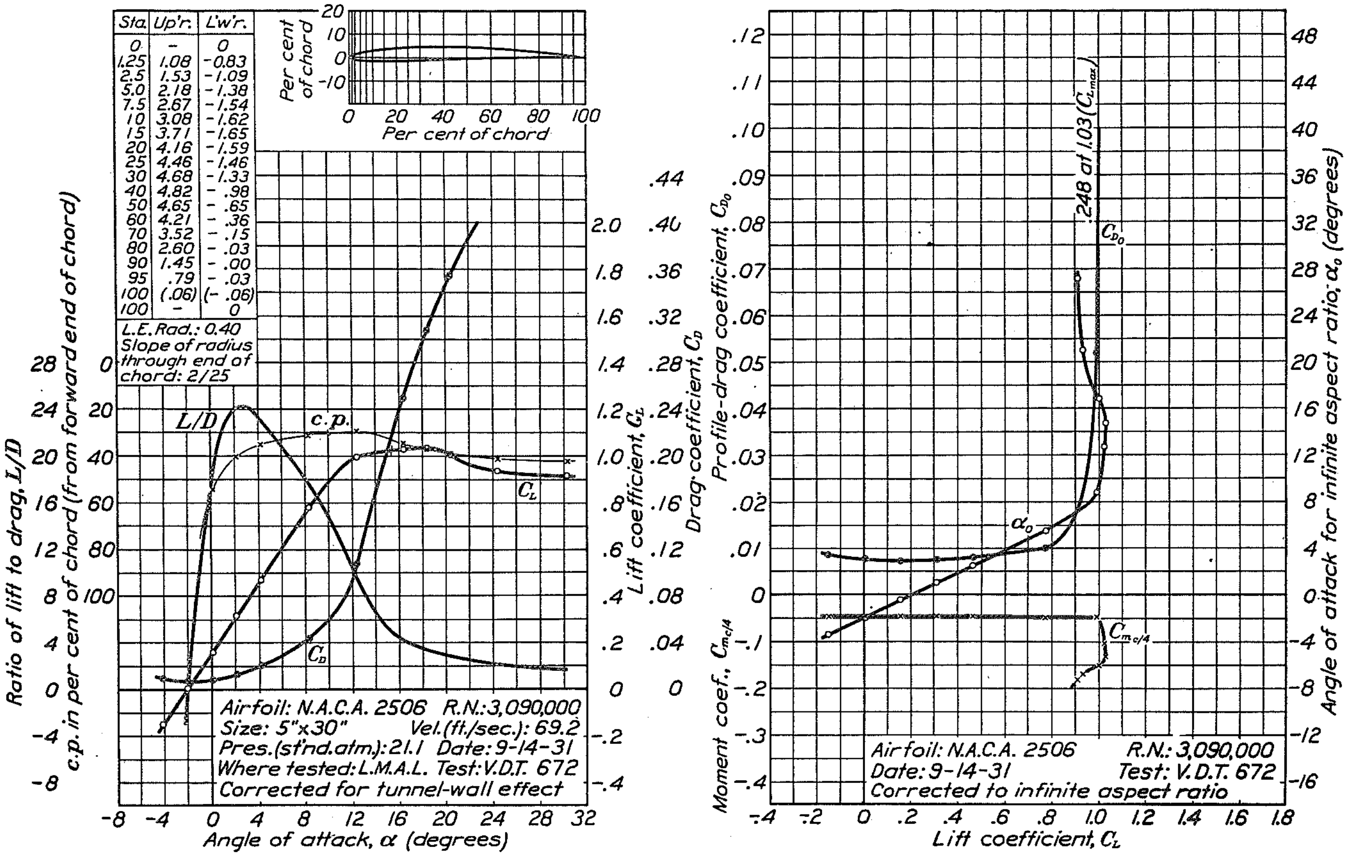
Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.87	-2.82
2.5	5.21	-4.02
5.0	7.00	-5.51
7.5	8.29	-6.48
10	9.28	-7.18
15	10.70	-8.05
20	11.59	-8.52
25	12.15	-8.67
30	12.38	-8.62
40	12.16	-8.16
50	11.22	-7.31
60	9.79	-6.17
70	7.94	-4.87
80	5.74	-3.44
90	3.18	-1.88
95	1.76	-1.06
100	(.22)	(-.22)
100	—	0

L.E. Rad.: 4.85
Slope of radius through end of chord: 2/20

Airfoil: N.A.C.A. 2421 R.N.: 3,000,000
Size: 5"x30" Vel.(ft./sec.): 70.5
Pres.(st'nd.atm.): 20.6 Date: 9-11-31
Where tested: L.M.A.L. Test: V.D.T. 670
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 2421 R.N.: 3,000,000
Date: 9-11-31 Test: V.D.T. 670
Corrected to infinite aspect ratio

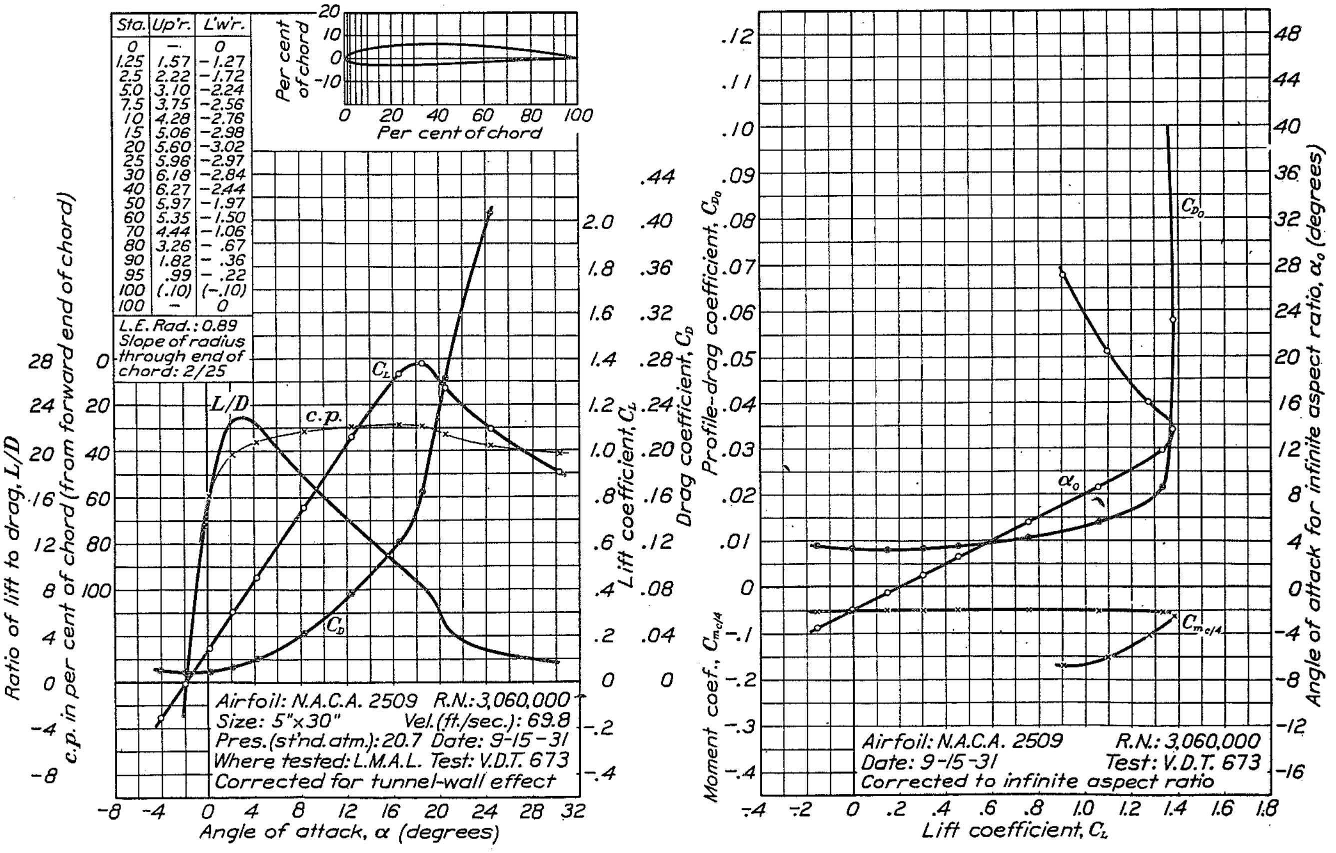
FIGURE 21.—N.A.C.A. 2421 airfoil.



Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.08	-0.83
2.5	1.53	-1.09
5.0	2.18	-1.38
7.5	2.67	-1.54
10	3.08	-1.62
15	3.71	-1.65
20	4.16	-1.59
25	4.46	-1.46
30	4.68	-1.33
40	4.82	- .98
50	4.65	- .65
60	4.21	- .36
70	3.52	- .15
80	2.60	- .03
90	1.45	- .00
95	.79	- .03
100	(.06)	(- .06)
100	–	0

L.E. Rad.: 0.40
Slope of radius through end of chord: 2/25

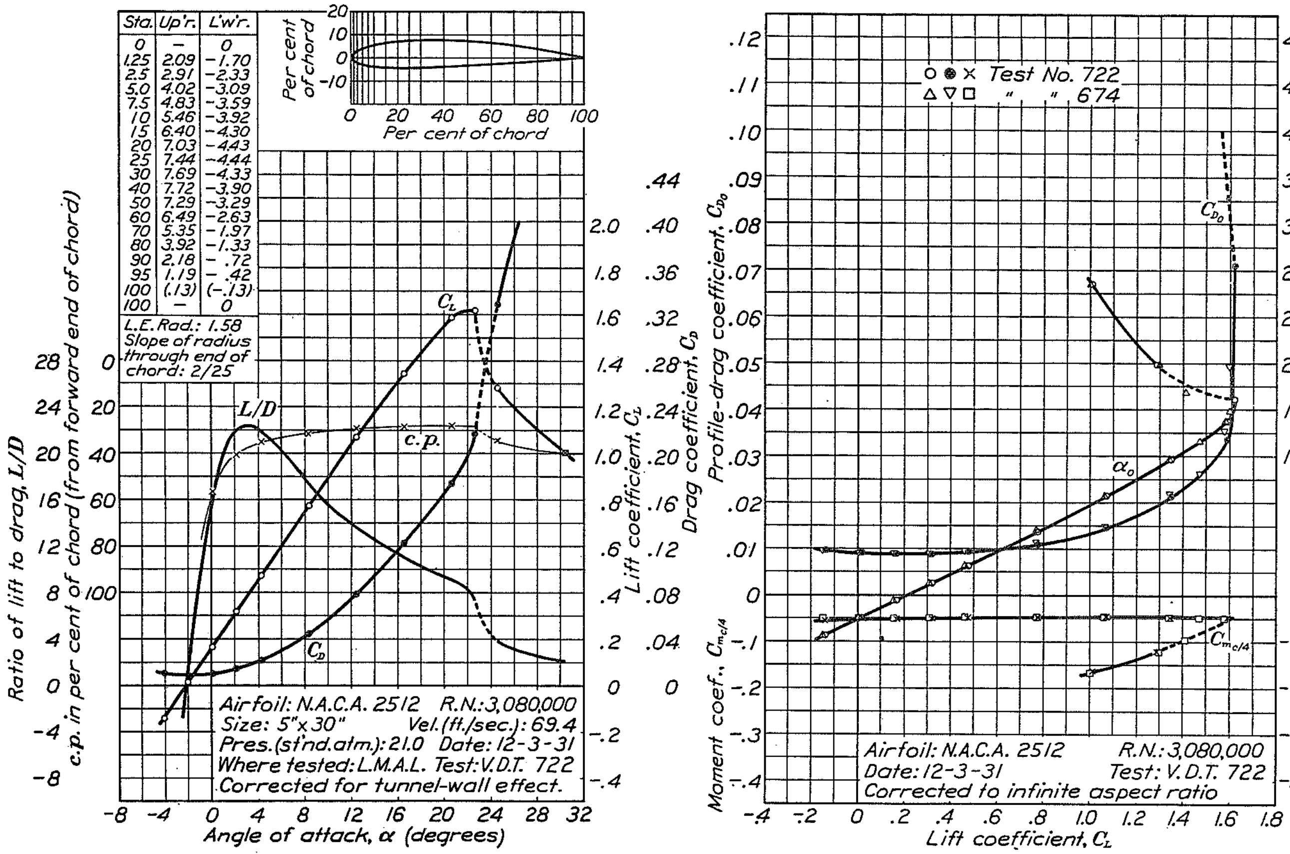
FIGURE 22.—N.A.C.A. 2506 airfoil.



Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.57	-1.27
2.5	2.22	-1.72
5.0	3.10	-2.24
7.5	3.75	-2.56
10	4.28	-2.76
15	5.06	-2.98
20	5.60	-3.02
25	5.96	-2.97
30	6.18	-2.84
40	6.27	-2.44
50	5.97	-1.97
60	5.35	-1.50
70	4.44	-1.06
80	3.26	- .67
90	1.82	- .36
95	.99	- .22
100	(.10)	(-.10)
100	–	0

L.E. Rad.: 0.89
Slope of radius through end of chord: 2/25

FIGURE 23.—N.A.C.A. 2509 airfoil.



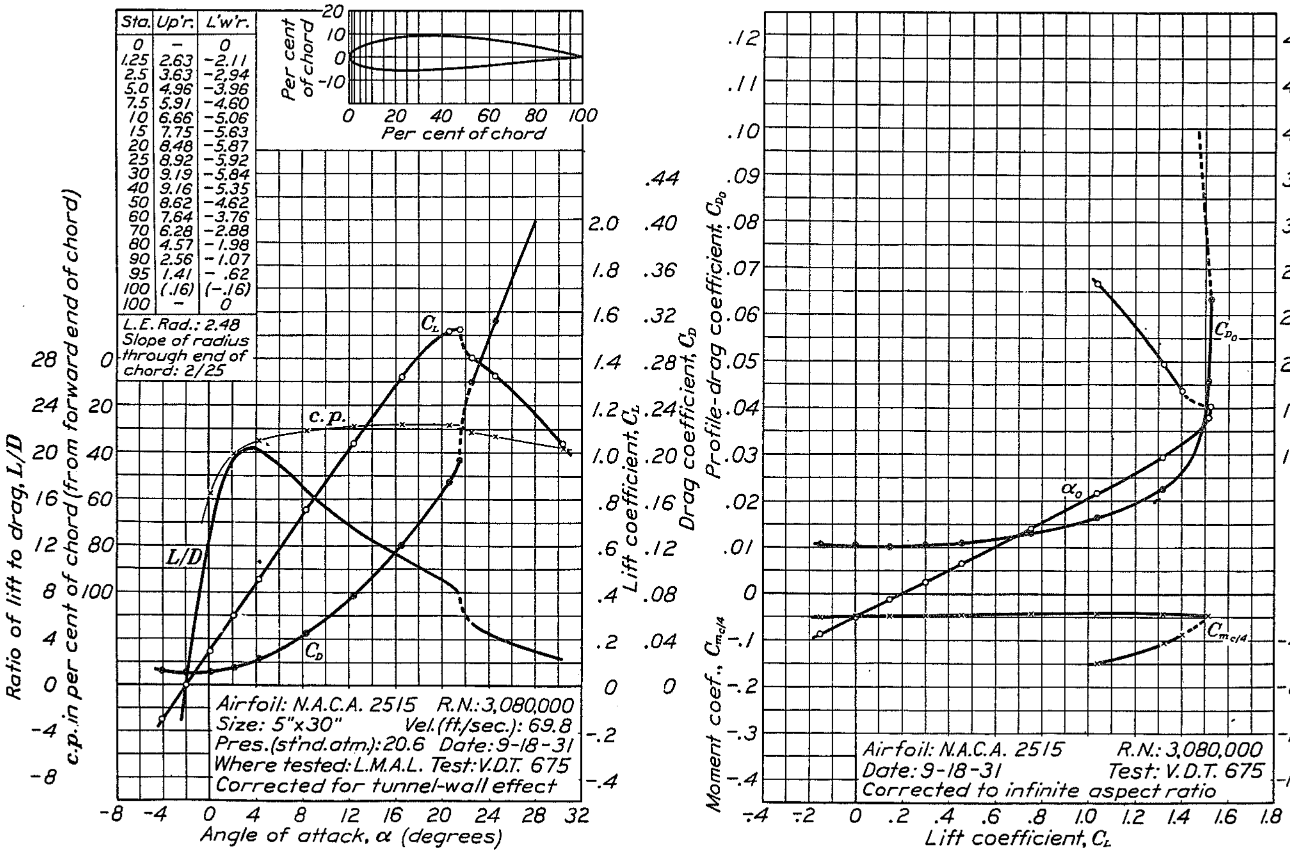
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.09	-1.70
2.5	2.91	-2.33
5.0	4.02	-3.09
7.5	4.83	-3.59
10	5.46	-3.92
15	6.40	-4.30
20	7.03	-4.43
25	7.44	-4.44
30	7.69	-4.33
40	7.72	-3.90
50	7.29	-3.29
60	6.49	-2.63
70	5.35	-1.97
80	3.92	-1.33
90	2.18	- .72
95	1.19	- .42
100	(.13)	(-.13)
100	–	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 2/25

Airfoil: N.A.C.A. 2512 R.N.: 3,080,000
Size: 5"x 30" Vel. (ft./sec.): 69.4
Pres. (st'nd. atm.): 21.0 Date: 12-3-31
Where tested: L.M.A.L. Test: V.D.T. 722
Corrected for tunnel-wall effect.

Airfoil: N.A.C.A. 2512 R.N.: 3,080,000
Date: 12-3-31 Test: V.D.T. 722
Corrected to infinite aspect ratio

FIGURE 24.—N.A.C.A. 2512 airfoil.



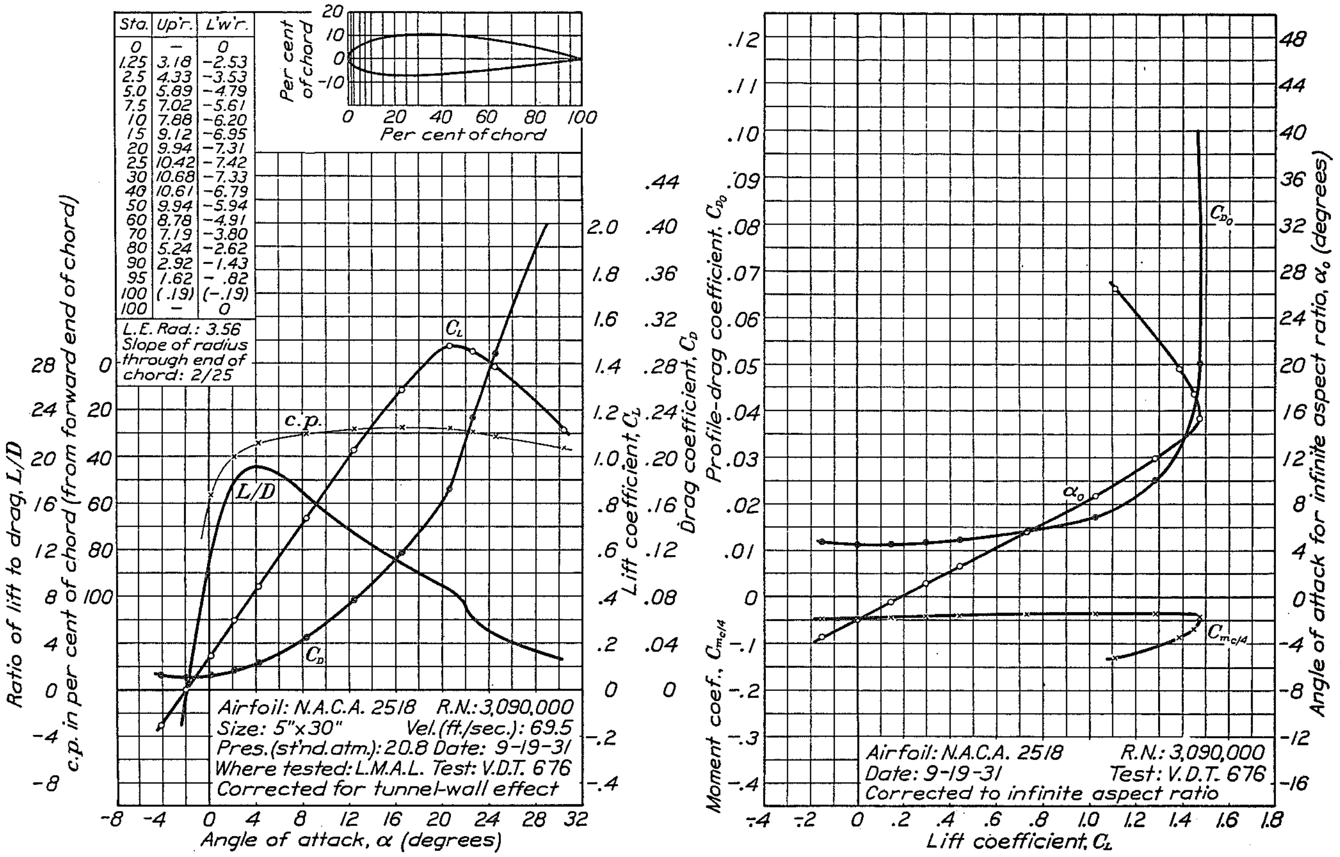
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.63	-2.11
2.5	3.63	-2,94
5.0	4.96	-3.96
7.5	5.91	-4.60
10	6.66	-5.06
15	7.75	-5.63
20	8.48	-5.87
25	8.92	-5.92
30	9.19	-5.84
40	9.16	-5.35
50	8.62	-4.62
60	7.64	-3.76
70	6.28	-2.88
80	4.57	-1.98
90	2.56	-1.07
95	1.41	- .62
100	(.16)	(-.16)
100	–	0

L.E. Rad.: 2.48
Slope of radius through end of chord: 2/25

Airfoil: N.A.C.A. 2515 R.N.: 3,080,000
Size: 5"x 30" Vel. (ft./sec.): 69.8
Pres. (st'nd. atm.): 20.6 Date: 9-18-31
Where tested: L.M.A.L. Test: V.D.T. 675
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2515 R.N.: 3,080,000
Date: 9-18-31 Test: V.D.T. 675
Corrected to infinite aspect ratio

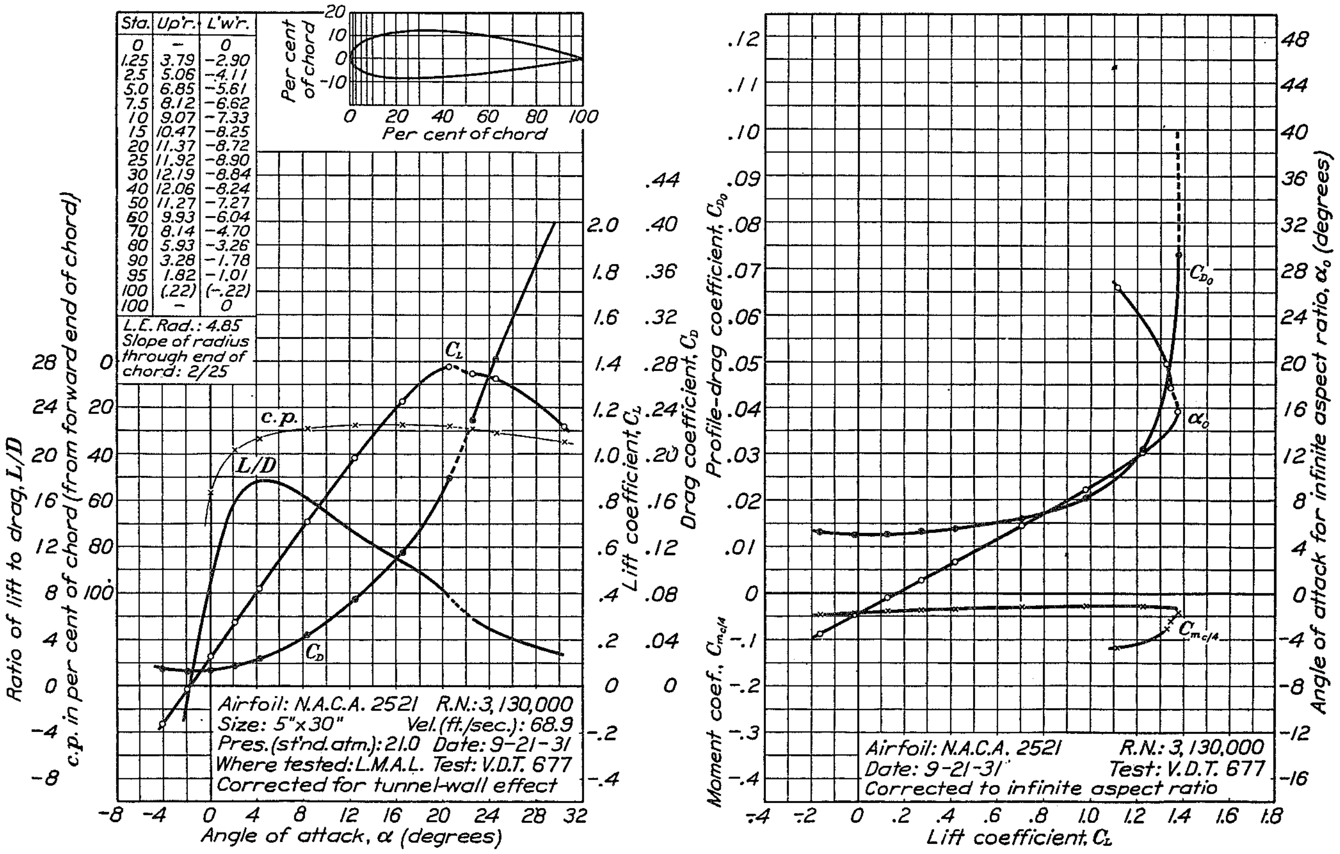
FIGURE 25.—N.A.C.A. 2515 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.18	-2.53
2.5	4.33	-3.53
5.0	5.89	-4.79
7.5	7.02	-5.61
10	7.88	-6.20
15	9.12	-6.95
20	9.94	-7.31
25	10.42	-7.42
30	10.68	-7.33
40	10.61	-6.79
50	9.94	-5.94
60	8.78	-4.91
70	7.19	-3.80
80	5.24	-2.62
90	2.92	-1.43
95	1.62	- .82
100	(.19)	(-.19)
100	—	0

L.E. Rad.: 3.56
Slope of radius through end of chord: 2/25

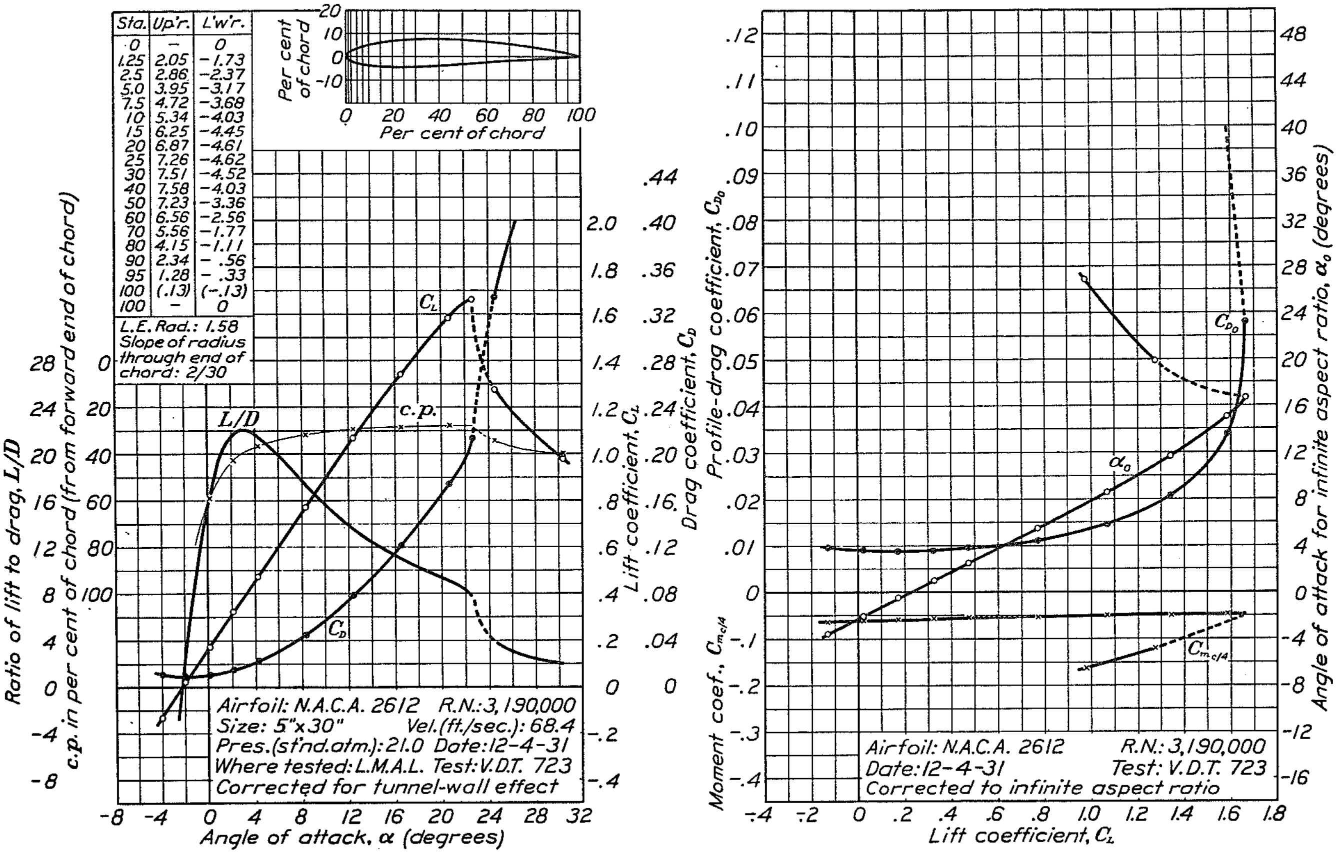
FIGURE 26.—N.A.C.A. 2518 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.79	-2.90
2.5	5.06	-4.11
5.0	6.85	-5.61
7.5	8.12	-6.62
10	9.07	-7.33
15	10.47	-8.25
20	11.37	-8.72
25	11.92	-8.90
30	12.19	-8.84
40	12.06	-8.24
50	11.27	-7.27
60	9.93	-6.04
70	8.14	-4.70
80	5.93	-3.26
90	3.28	-1.78
95	1.82	-1.01
100	(.22)	(-.22)
100	—	0

L.E. Rad.: 4.85
Slope of radius through end of chord: 2/25

FIGURE 27.—N.A.C.A. 2521 airfoil.



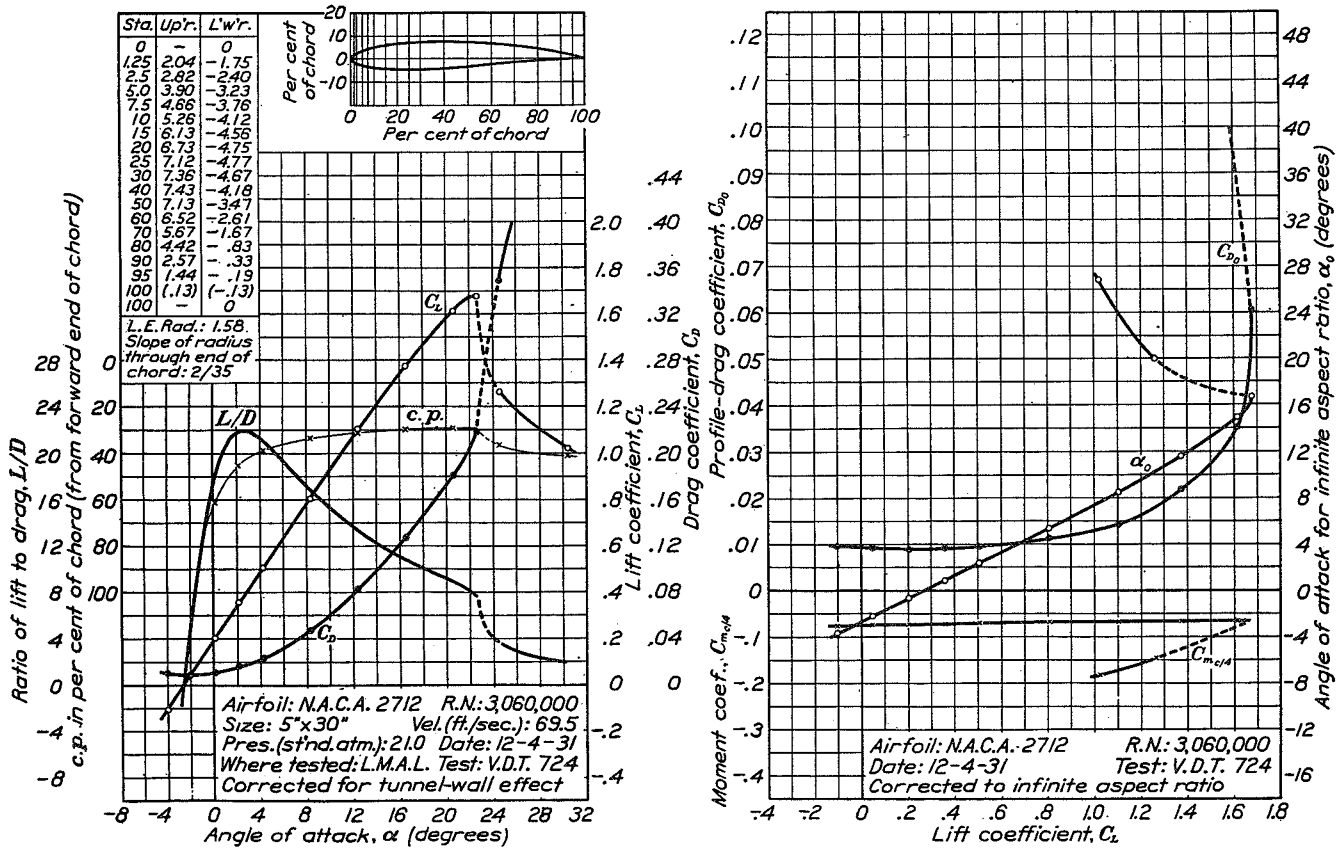
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.05	–1.73
2.5	2.86	–2.37
5.0	3.95	–3.17
7.5	4.72	–3.68
10	5.34	–4.03
15	6.25	–4.45
20	6.87	–4.61
25	7.26	–4.62
30	7.51	–4.52
40	7.58	–4.03
50	7.23	–3.36
60	6.56	–2.56
70	5.56	–1.77
80	4.15	–1.11
90	2.34	– .56
95	1.28	– .33
100	(.13)	(–.13)
100	–	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 2/30

Airfoil: N.A.C.A. 2612 R.N.: 3,190,000
Size: 5"x30" Vel.(ft./sec.): 68.4
Pres.(st'nd.atm.): 21.0 Date: 12-4-31
Where tested: L.M.A.L. Test: V.D.T. 723
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2612 R.N.: 3,190,000
Date: 12-4-31 Test: V.D.T. 723
Corrected to infinite aspect ratio

FIGURE 28.—N.A.C.A. 2612 airfoil.



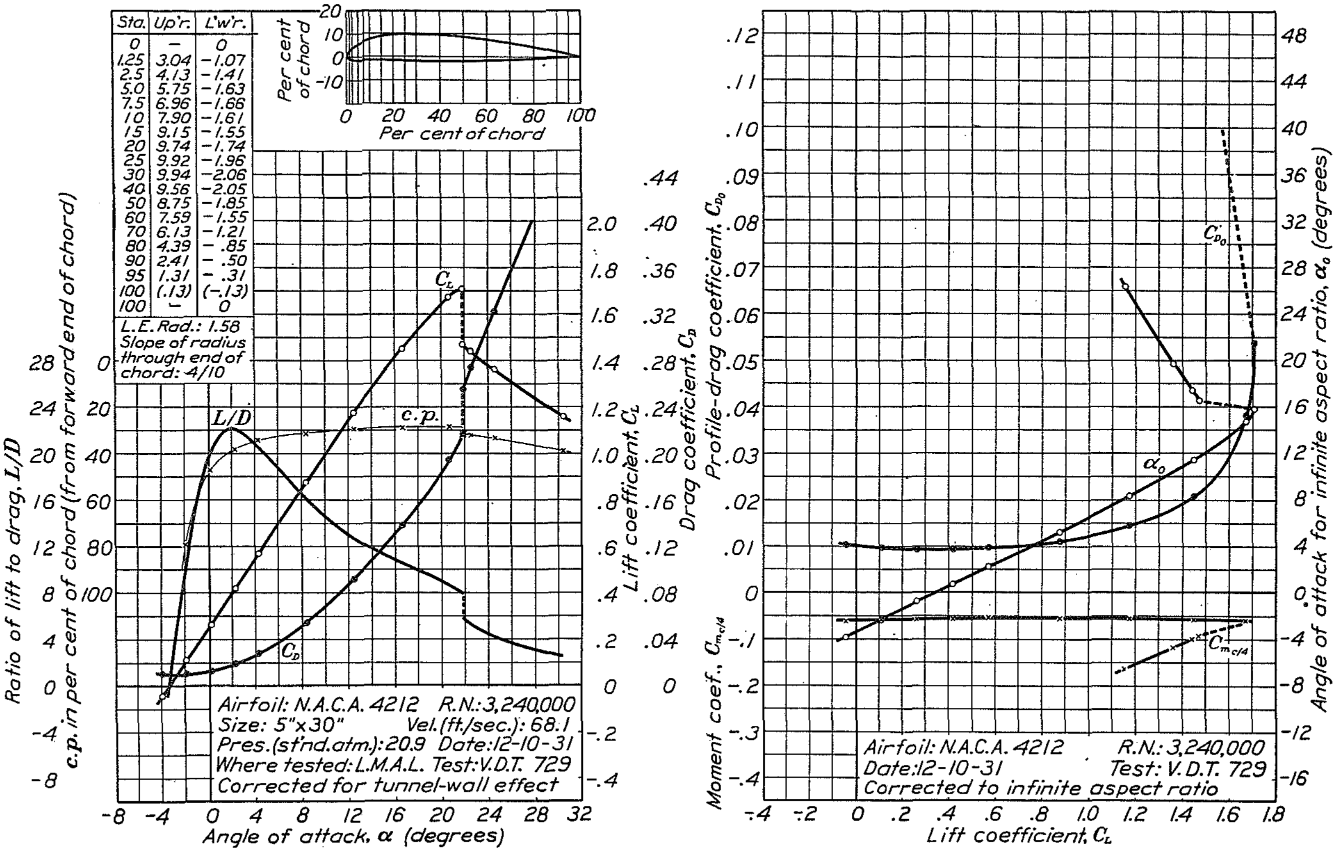
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.04	–1.75
2.5	2.82	–2.40
5.0	3.90	–3.23
7.5	4.66	–3.76
10	5.26	–4.12
15	6.13	–4.56
20	6.73	–4.75
25	7.12	–4.77
30	7.36	–4.67
40	7.43	–4.18
50	7.13	–3.47
60	6.52	–2.61
70	5.67	–1.67
80	4.42	– .83
90	2.57	– .33
95	1.44	– .19
100	(.13)	(–.13)
100	–	0

L.E. Rad.: 1.58.
Slope of radius through end of chord: 2/35

Airfoil: N.A.C.A. 2712 R.N.: 3,060,000
Size: 5"x30" Vel.(ft./sec.): 69.5
Pres.(st'nd.atm.): 21.0 Date: 12-4-31
Where tested: L.M.A.L. Test: V.D.T. 724
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 2712 R.N.: 3,060,000
Date: 12-4-31 Test: V.D.T. 724
Corrected to infinite aspect ratio

FIGURE 29.—N.A.C.A. 2712 airfoil.



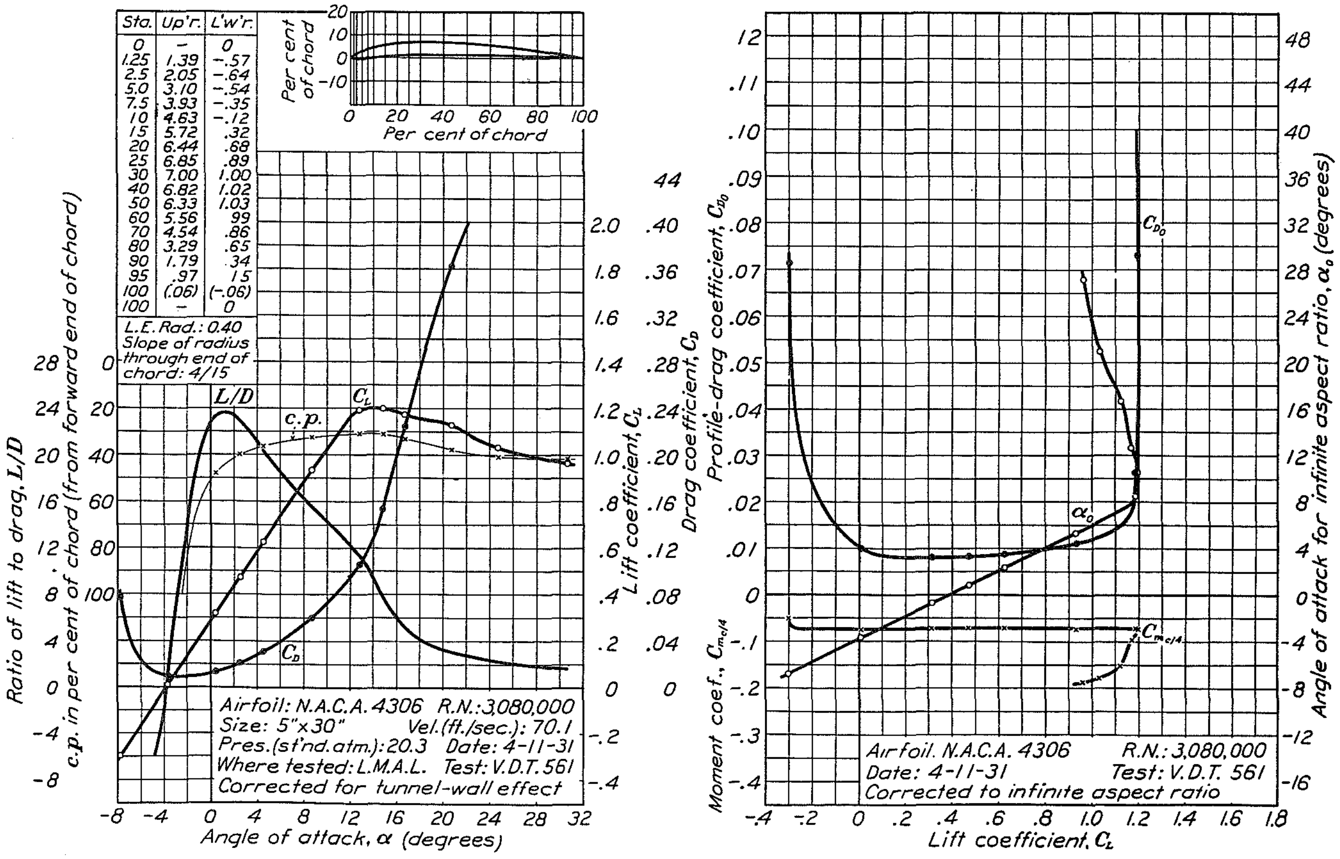
Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.04	−1.07
2.5	4.13	−1.41
5.0	5.75	−1.63
7.5	6.96	−1.66
10	7.90	−1.61
15	9.15	−1.55
20	9.74	−1.74
25	9.92	−1.96
30	9.94	−2.06
40	9.56	−2.05
50	8.75	−1.85
60	7.59	−1.55
70	6.13	−1.21
80	4.39	− .85
90	2.41	− .50
95	1.31	− .31
100	(.13)	(−.13)
100	—	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 4/10

Airfoil: N.A.C.A. 4212 R.N.: 3,240,000
Size: 5"x30" Vel.(ft./sec.): 68.1
Pres.(st'nd.atm.): 20.9 Date: 12-10-31
Where tested: L.M.A.L. Test: V.D.T. 729
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4212 R.N.: 3,240,000
Date: 12-10-31 Test: V.D.T. 729
Corrected to infinite aspect ratio

FIGURE 30.—N.A.C.A. 4212 airfoil.



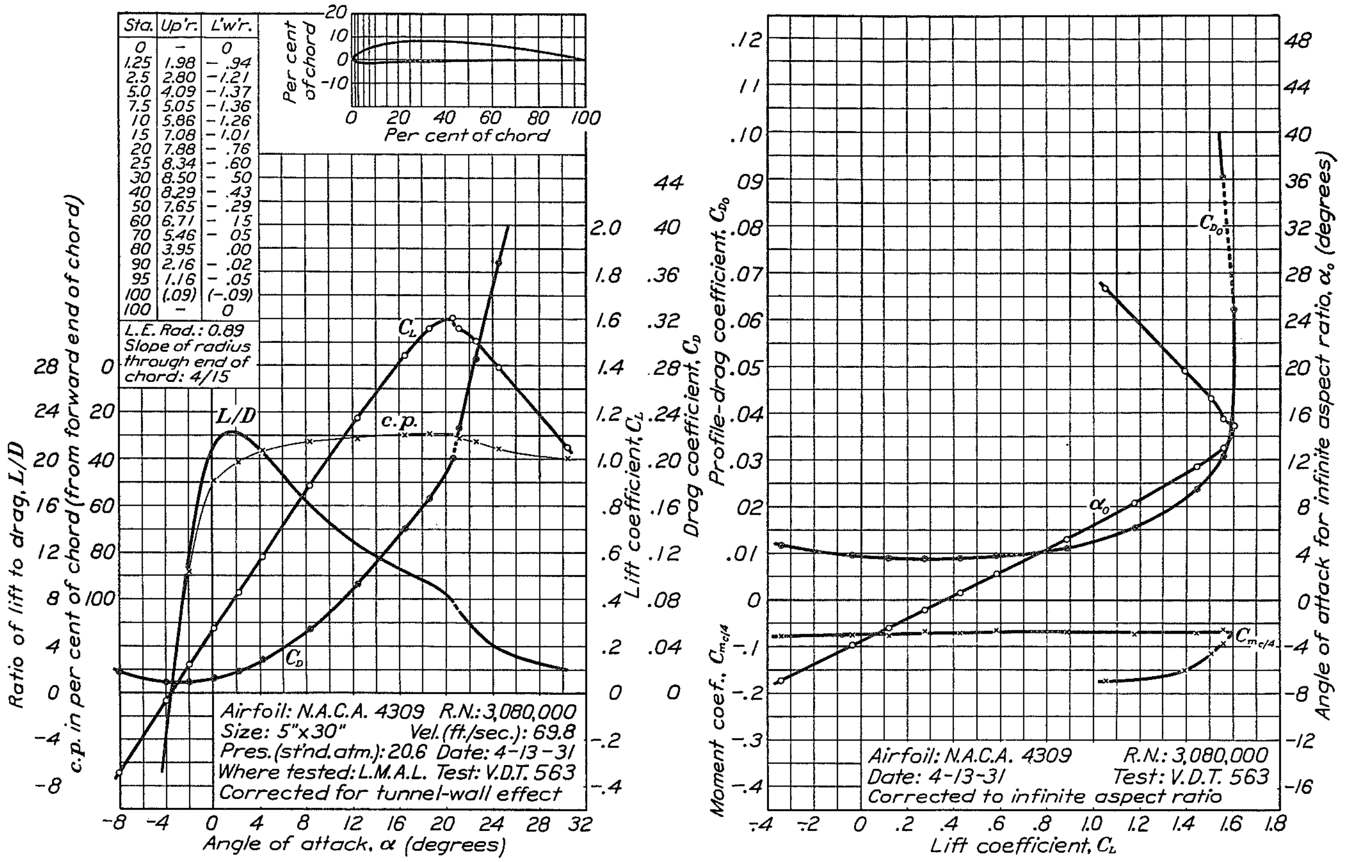
Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.39	−.57
2.5	2.05	−.64
5.0	3.10	−.54
7.5	3.93	−.35
10	4.63	−.12
15	5.72	.32
20	6.44	.68
25	6.85	.89
30	7.00	1.00
40	6.82	1.02
50	6.33	1.03
60	5.56	99
70	4.54	.86
80	3.29	.65
90	1.79	.34
95	.97	15
100	(.06)	(−.06)
100	—	0

L.E. Rad.: 0.40
Slope of radius through end of chord: 4/15

Airfoil: N.A.C.A. 4306 R.N.: 3,080,000
Size: 5"x30" Vel.(ft./sec.): 70.1
Pres.(st'nd.atm.): 20.3 Date: 4-11-31
Where tested: L.M.A.L. Test: V.D.T. 561
Corrected for tunnel-wall effect

Airfoil. N.A.C.A. 4306 R.N.: 3,080,000
Date: 4-11-31 Test: V.D.T. 561
Corrected to infinite aspect ratio

FIGURE 31.—N.A.C.A. 4306 airfoil.



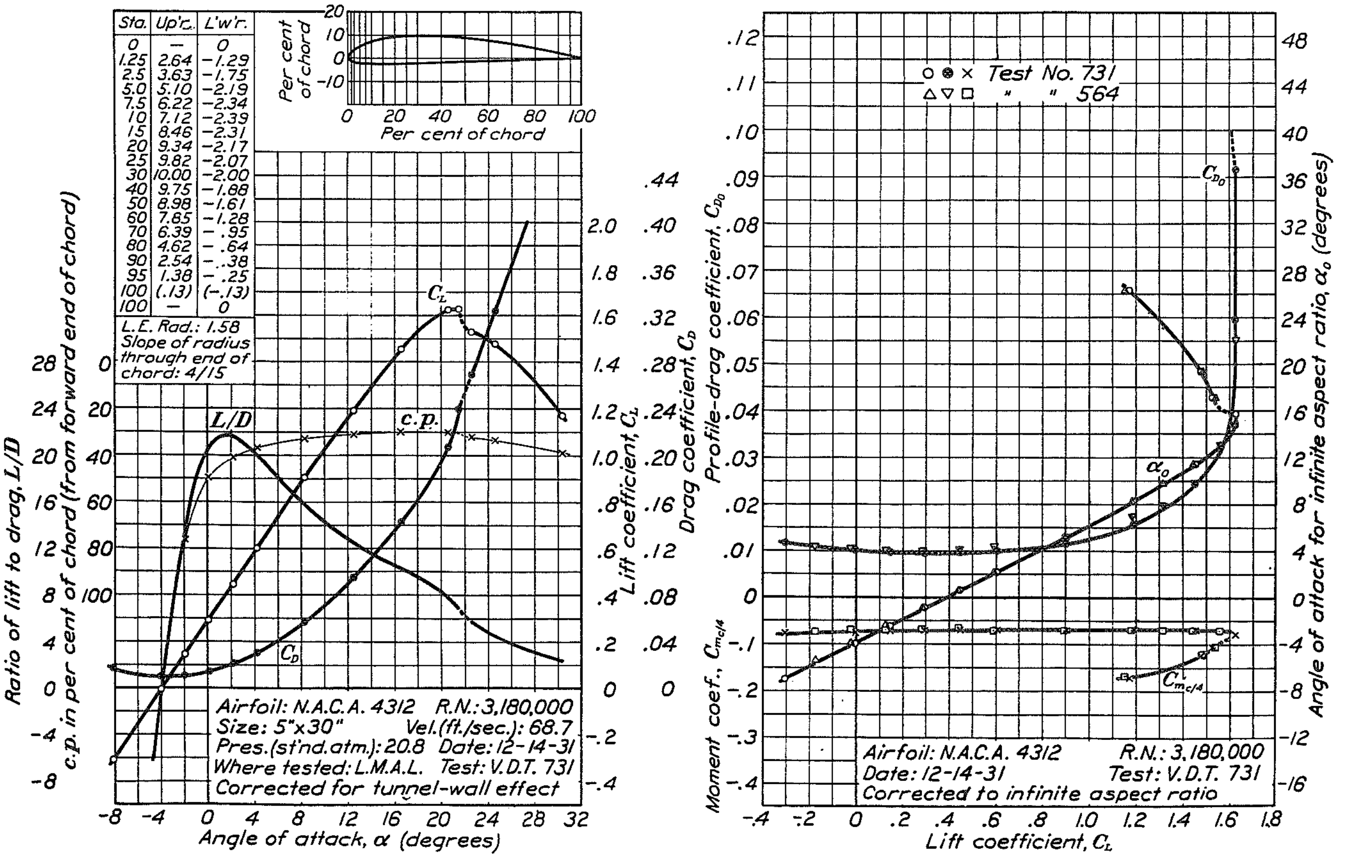
Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.98	– .94
2.5	2.80	–1.21
5.0	4.09	–1.37
7.5	5.05	–1.36
10	5.86	–1.26
15	7.08	–1.01
20	7.88	– .76
25	8.34	– .60
30	8.50	– 50
40	8.29	– .43
50	7.65	– .29
60	6.71	– 15
70	5.46	– 05
80	3.95	.00
90	2.16	– .02
95	1.16	– .05
100	(.09)	(–.09)
100	–	0

L.E. Rad.: 0.89
Slope of radius through end of chord: 4/15

Airfoil: N.A.C.A. 4309 R.N.: 3,080,000
Size: 5"x30" Vel.(ft./sec.): 69.8
Pres.(st'nd.atm.): 20.6 Date: 4-13-31
Where tested: L.M.A.L. Test: V.D.T. 563
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4309 R.N.: 3,080,000
Date: 4-13-31 Test: V.D.T. 563
Corrected to infinite aspect ratio

FIGURE 32.—N.A.C.A. 4309 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.64	–1.29
2.5	3.63	–1.75
5.0	5.10	–2.19
7.5	6.22	–2.34
10	7.12	–2.39
15	8.46	–2.31
20	9.34	–2.17
25	9.82	–2.07
30	10.00	–2.00
40	9.75	–1.88
50	8.98	–1.61
60	7.65	–1.28
70	6.39	– .95
80	4.62	– .64
90	2.54	– .38
95	1.38	– .25
100	(.13)	(–.13)
100	—	0

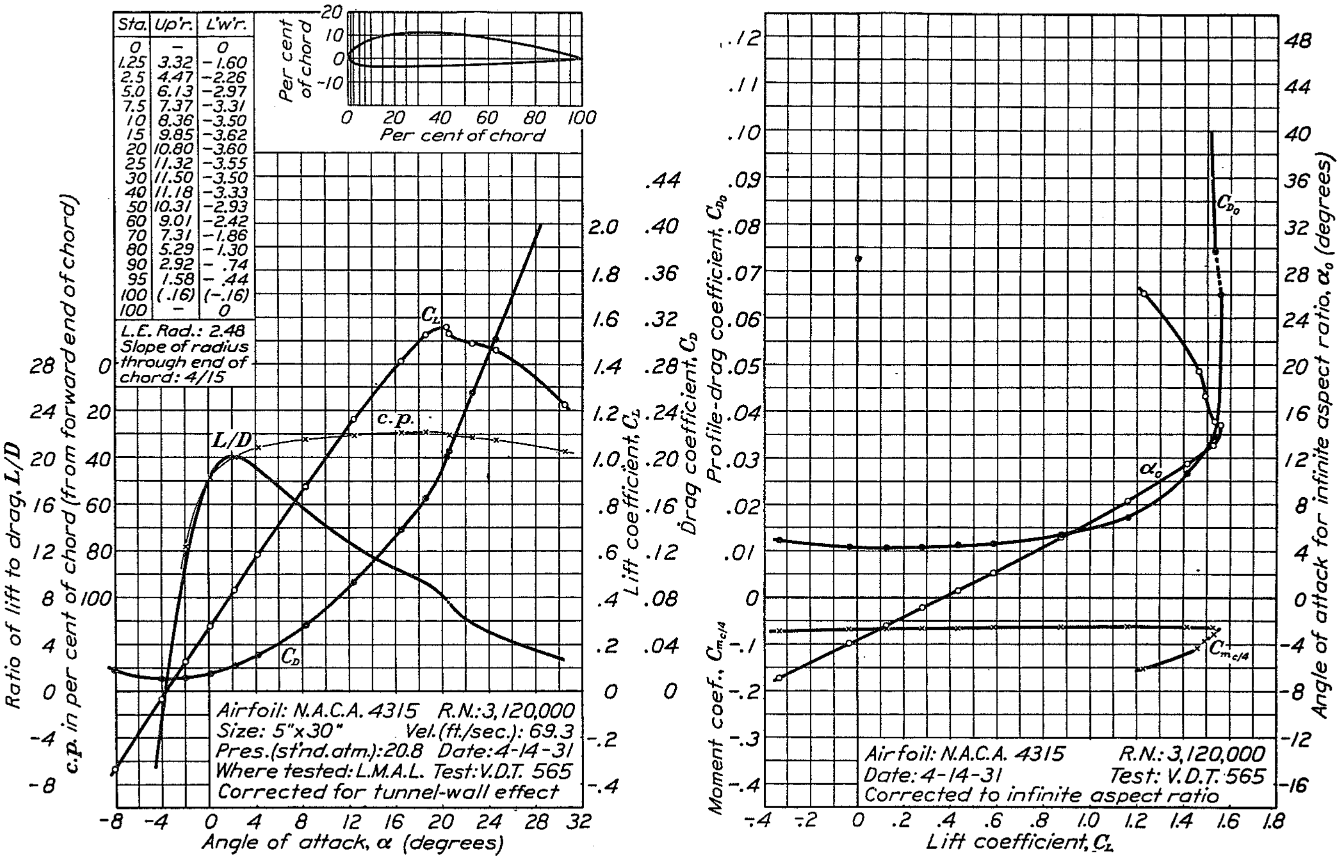
L.E. Rad.: 1.58
Slope of radius through end of chord: 4/15

Airfoil: N.A.C.A. 4312 R.N.: 3,180,000
Size: 5"x30" Vel.(ft./sec.): 68.7
Pres.(st'nd.atm.): 20.8 Date: 12-14-31
Where tested: L.M.A.L. Test: V.D.T. 731
Corrected for tunnel-wall effect

○ ⊗ × Test No. 731
△ ▽ □ " " 564

Airfoil: N.A.C.A. 4312 R.N.: 3,180,000
Date: 12-14-31 Test: V.D.T. 731
Corrected to infinite aspect ratio

FIGURE 33.—N.A.C.A. 4312 airfoil.



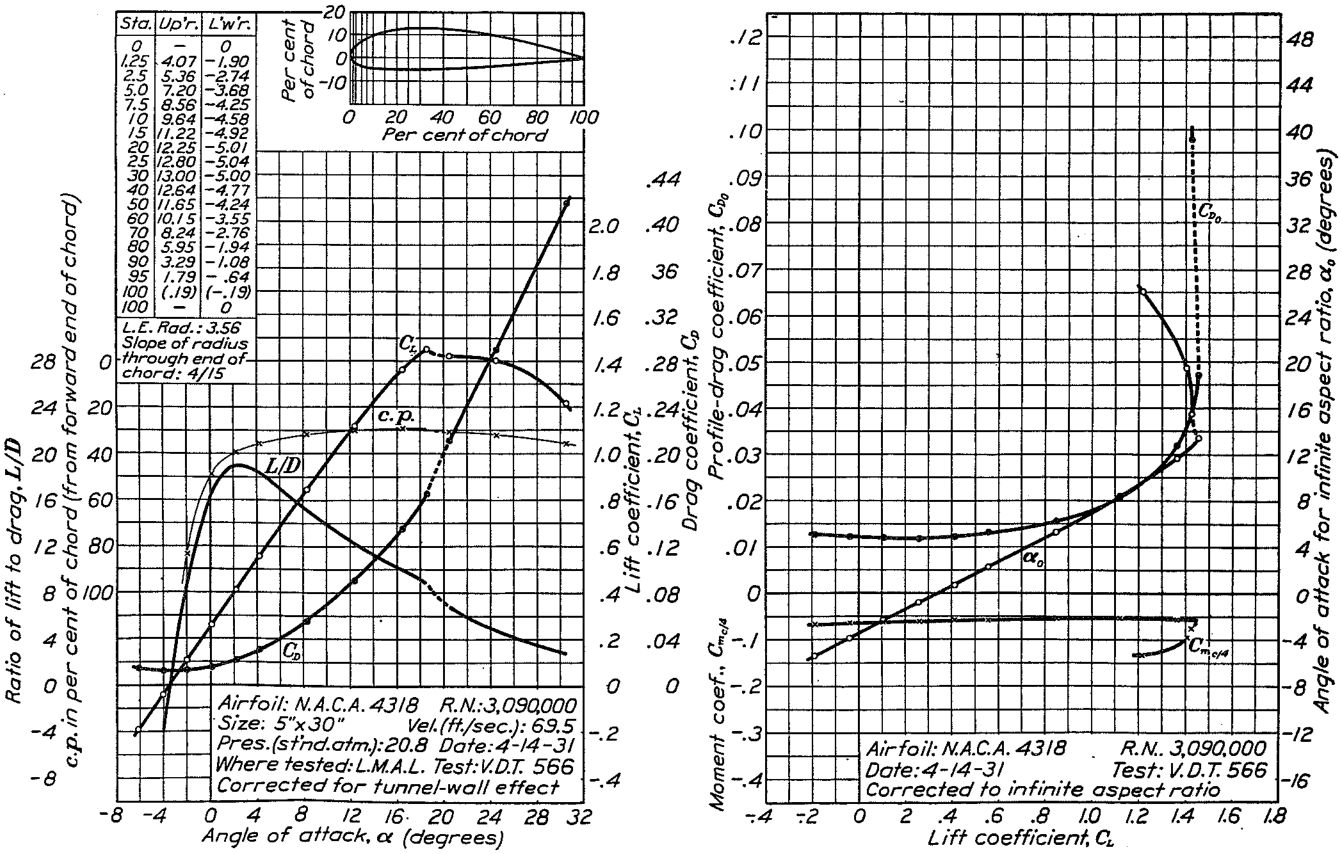
Sta.	Up'r.	L'w'r.
0	–	0
1.25	3.32	-1.60
2.5	4.47	-2.26
5.0	6.13	-2.97
7.5	7.37	-3.31
10	8.36	-3.50
15	9.85	-3.62
20	10.80	-3.60
25	11.32	-3.55
30	11.50	-3.50
40	11.18	-3.33
50	10.31	-2.93
60	9.01	-2.42
70	7.31	-1.86
80	5.29	-1.30
90	2.92	- .74
95	1.58	- .44
100	(.16)	(-.16)
100	–	0

L.E. Rad.: 2.48
Slope of radius through end of chord: 4/15

Airfoil: N.A.C.A. 4315 R.N.: 3,120,000
Size: 5"x30" Vel. (ft./sec.): 69.3
Pres. (st'nd. atm.): 20.8 Date: 4-14-31
Where tested: L.M.A.L. Test: V.D.T. 565
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4315 R.N.: 3,120,000
Date: 4-14-31 Test: V.D.T. 565
Corrected to infinite aspect ratio

FIGURE 34.—N.A.C.A. 4315 airfoil.



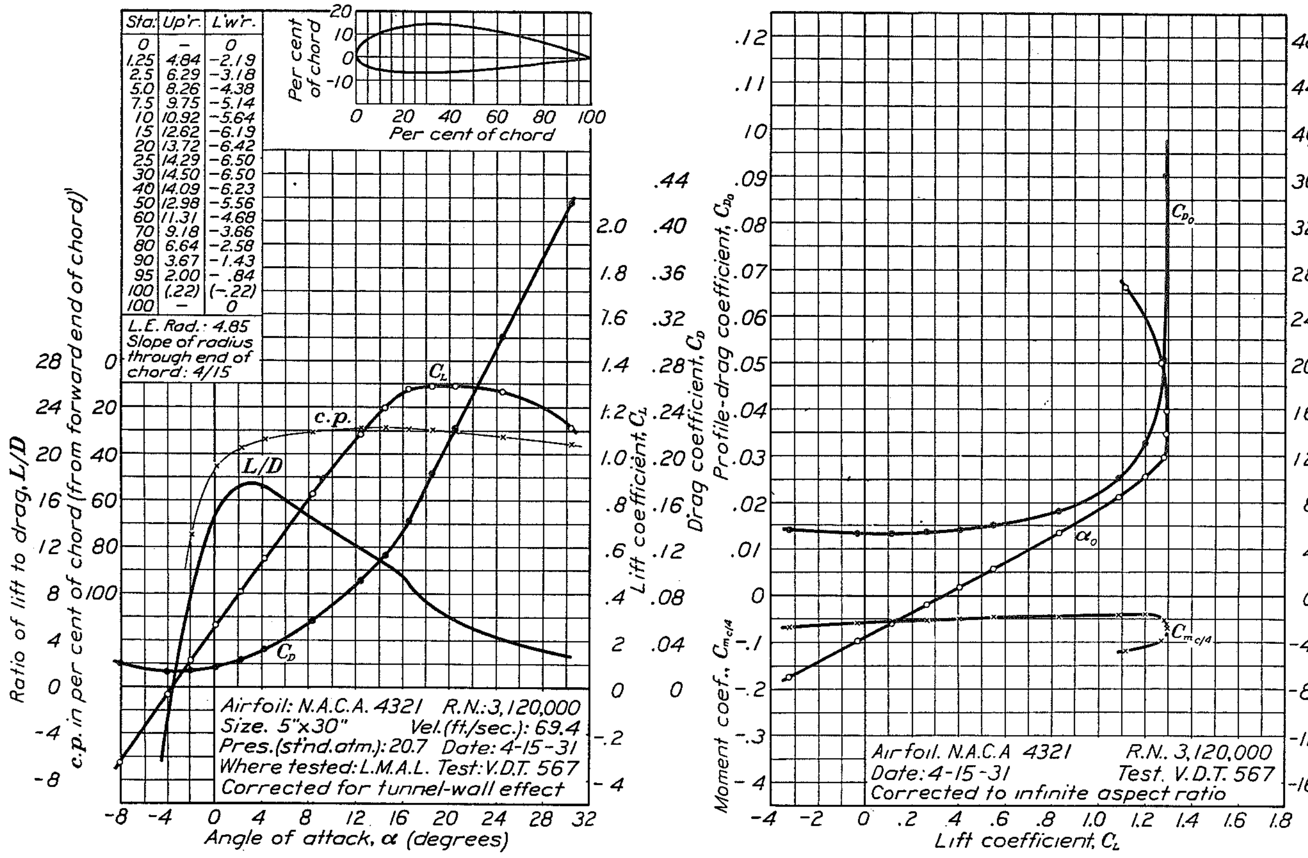
Sta.	Up'r.	L'w'r.
0	–	0
1.25	4.07	-1.90
2.5	5.36	-2.74
5.0	7.20	-3.68
7.5	8.56	-4.25
10	9.64	-4.58
15	11.22	-4.92
20	12.25	-5.01
25	12.80	-5.04
30	13.00	-5.00
40	12.64	-4.77
50	11.65	-4.24
60	10.15	-3.55
70	8.24	-2.76
80	5.95	-1.94
90	3.29	-1.08
95	1.79	- .64
100	(.19)	(-.19)
100	–	0

L.E. Rad.: 3.56
Slope of radius through end of chord: 4/15

Airfoil: N.A.C.A. 4318 R.N.: 3,090,000
Size: 5"x30" Vel. (ft./sec.): 69.5
Pres. (st'nd. atm.): 20.8 Date: 4-14-31
Where tested: L.M.A.L. Test: V.D.T. 566
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4318 R.N. 3,090,000
Date: 4-14-31 Test: V.D.T. 566
Corrected to infinite aspect ratio

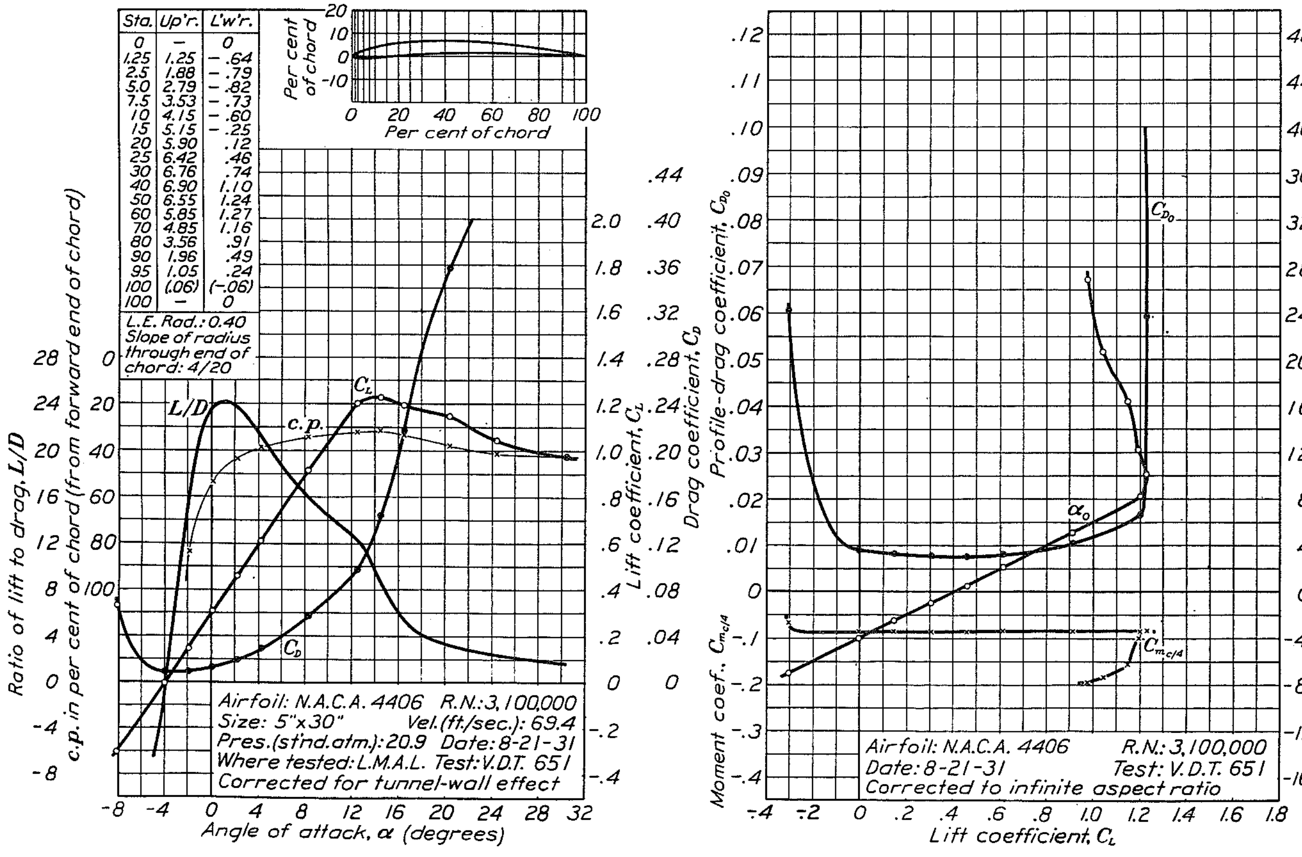
FIGURE 35.—N.A.C.A. 4318 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	4.84	−2.19
2.5	6.29	−3.18
5.0	8.26	−4.38
7.5	9.75	−5.14
10	10.92	−5.64
15	12.62	−6.19
20	13.72	−6.42
25	14.29	−6.50
30	14.50	−6.50
40	14.09	−6.23
50	12.98	−5.56
60	11.31	−4.68
70	9.18	−3.66
80	6.64	−2.58
90	3.67	−1.43
95	2.00	− .84
100	(.22)	(−.22)
100	—	0

L.E. Rad.: 4.85
Slope of radius through end of chord: 4/15

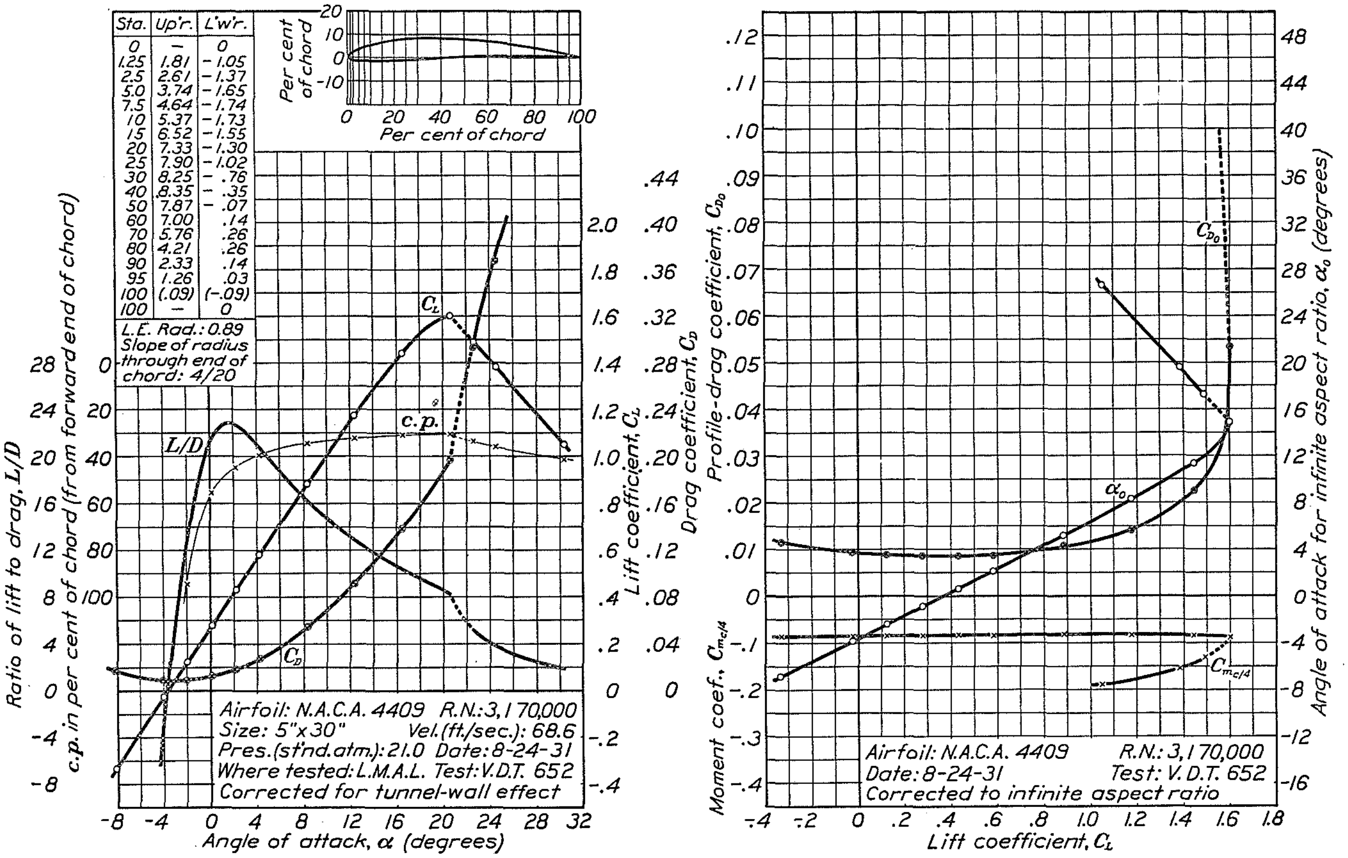
FIGURE 36.—N.A.C.A. 4321 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.25	− .64
2.5	1.88	− .79
5.0	2.79	− .82
7.5	3.53	− .73
10	4.15	− .60
15	5.15	− .25
20	5.90	.12
25	6.42	.46
30	6.76	.74
40	6.90	1.10
50	6.55	1.24
60	5.85	1.27
70	4.85	1.16
80	3.56	.91
90	1.96	.49
95	1.05	.24
100	(.06)	(−.06)
100	—	0

L.E. Rad.: 0.40
Slope of radius through end of chord: 4/20

FIGURE 37.—N.A.C.A. 4406 airfoil.



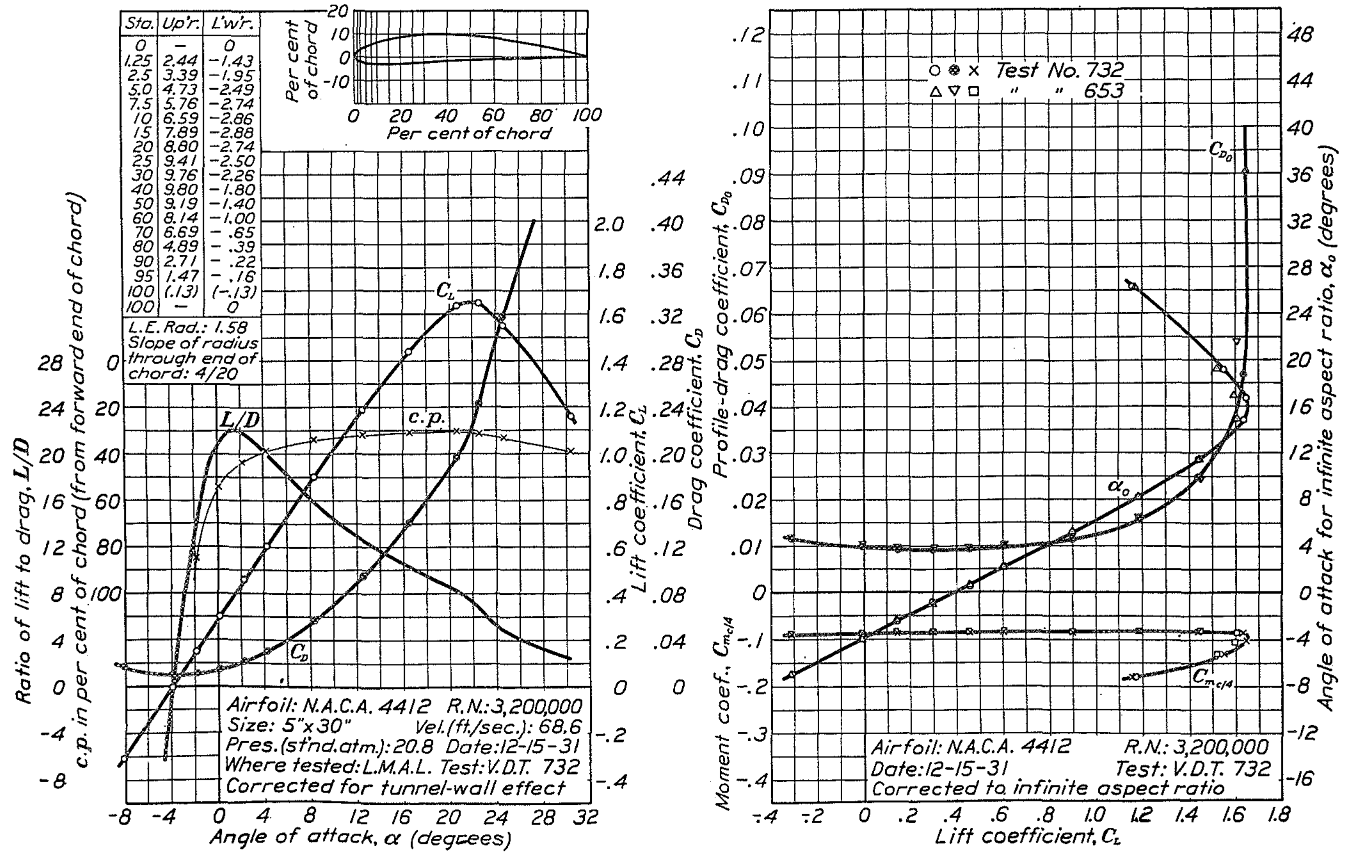
Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.81	-1.05
2.5	2.61	-1.37
5.0	3.74	-1.65
7.5	4.64	-1.74
10	5.37	-1.73
15	6.52	-1.55
20	7.33	-1.30
25	7.90	-1.02
30	8.25	- .76
40	8.35	- .35
50	7.87	- .07
60	7.00	.14
70	5.76	.26
80	4.21	.26
90	2.33	.14
95	1.26	.03
100	(.09)	(-.09)
100	—	0

L.E. Rad.: 0.89
Slope of radius through end of chord: 4/20

Airfoil: N.A.C.A. 4409 R.N.: 3,170,000
Size: 5"x30" Vel. (ft./sec.): 68.6
Pres. (st'nd. atm.): 21.0 Date: 8-24-31
Where tested: L.M.A.L. Test: V.D.T. 652
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4409 R.N.: 3,170,000
Date: 8-24-31 Test: V.D.T. 652
Corrected to infinite aspect ratio

FIGURE 38.—N.A.C.A. 4409 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.44	-1.43
2.5	3.39	-1.95
5.0	4.73	-2.49
7.5	5.76	-2.74
10	6.59	-2.86
15	7.89	-2.88
20	8.80	-2.74
25	9.41	-2.50
30	9.76	-2.26
40	9.80	-1.80
50	9.19	-1.40
60	8.14	-1.00
70	6.69	- .65
80	4.89	- .39
90	2.71	- .22
95	1.47	- .16
100	(.13)	(-.13)
100	—	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 4/20

Airfoil: N.A.C.A. 4412 R.N.: 3,200,000
Size: 5"x30" Vel. (ft./sec.): 68.6
Pres. (st'nd. atm.): 20.8 Date: 12-15-31
Where tested: L.M.A.L. Test: V.D.T. 732
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4412 R.N.: 3,200,000
Date: 12-15-31 Test: V.D.T. 732
Corrected to infinite aspect ratio

FIGURE 39.—N.A.C.A. 4412 airfoil.

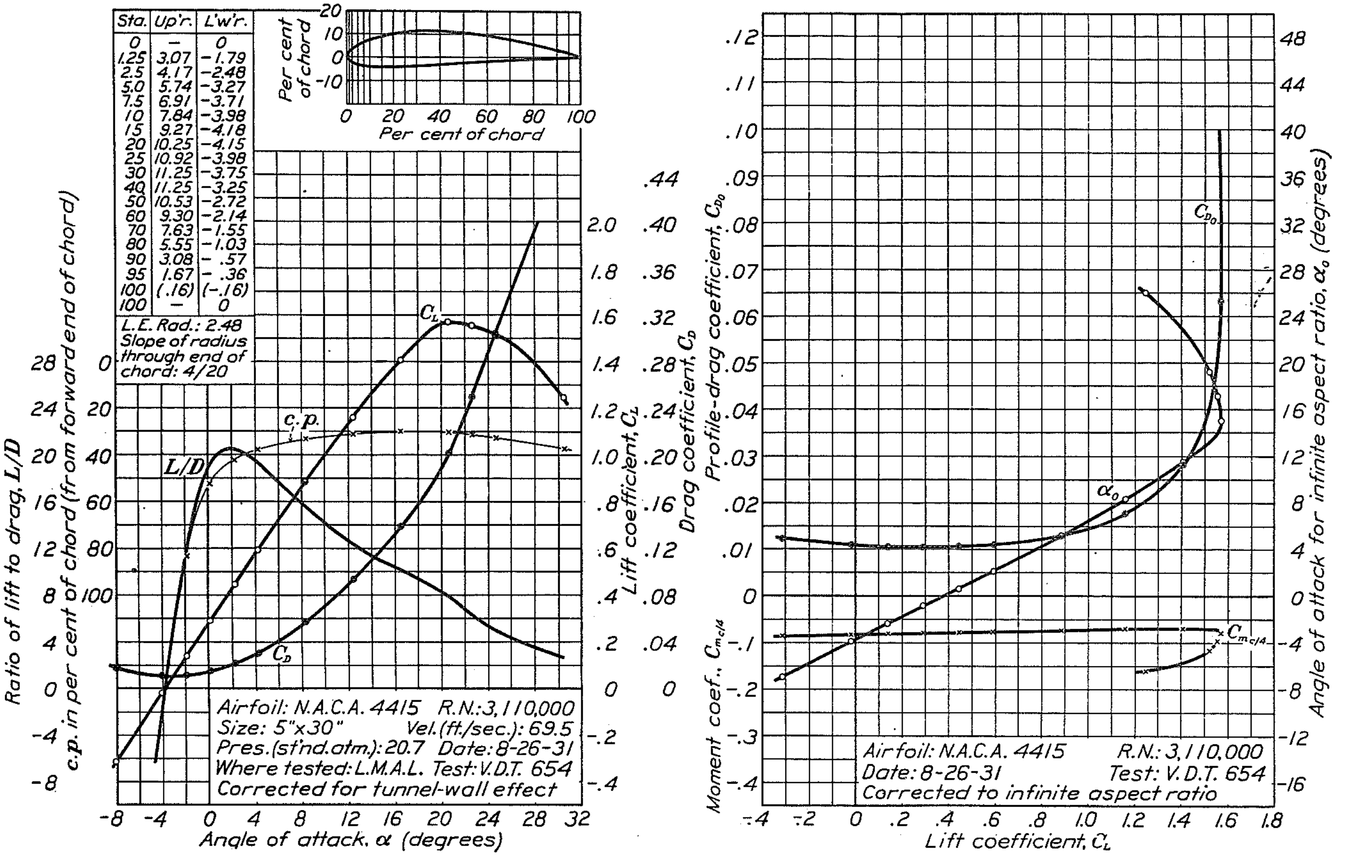


FIGURE 40.—N.A.C.A. 4415 airfoil.

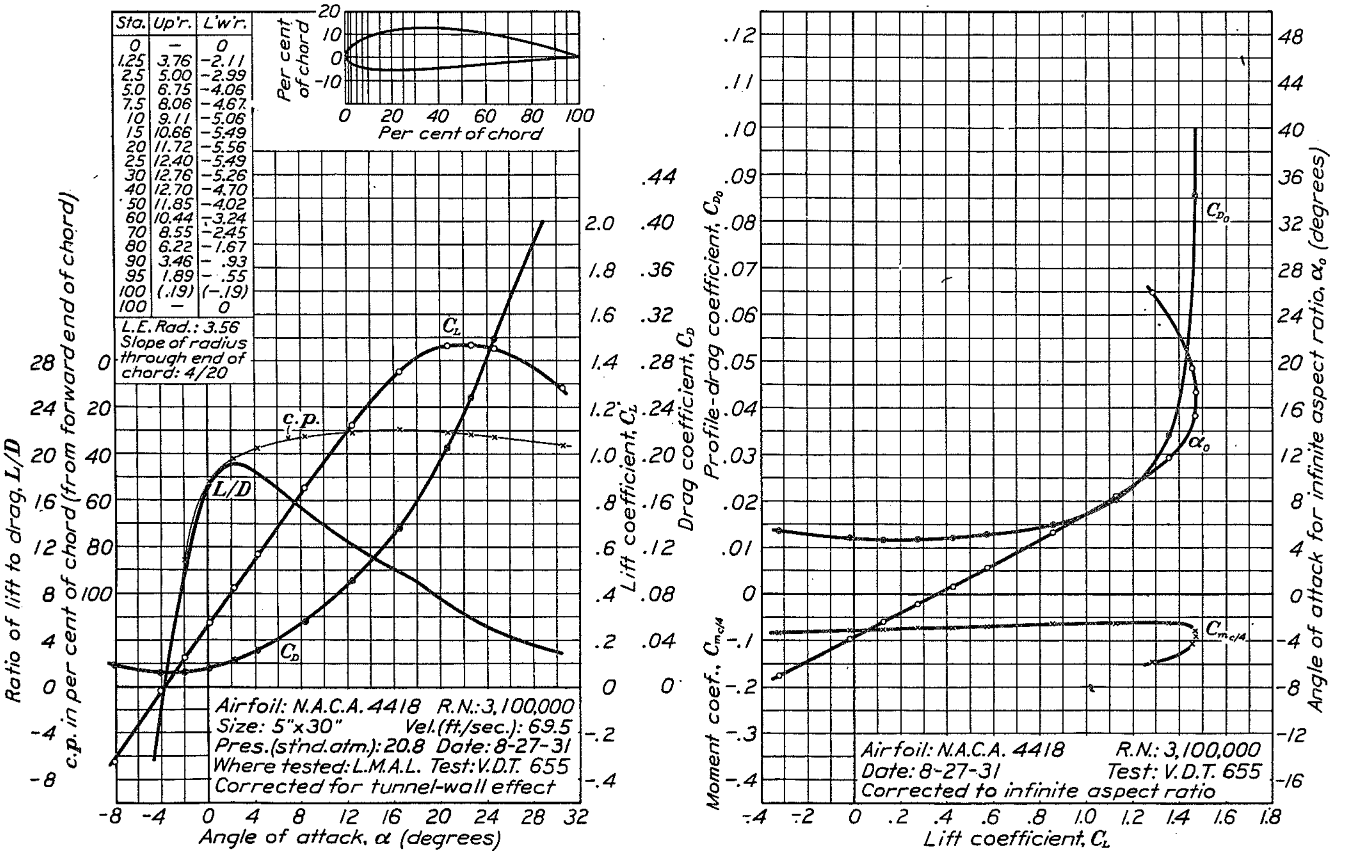
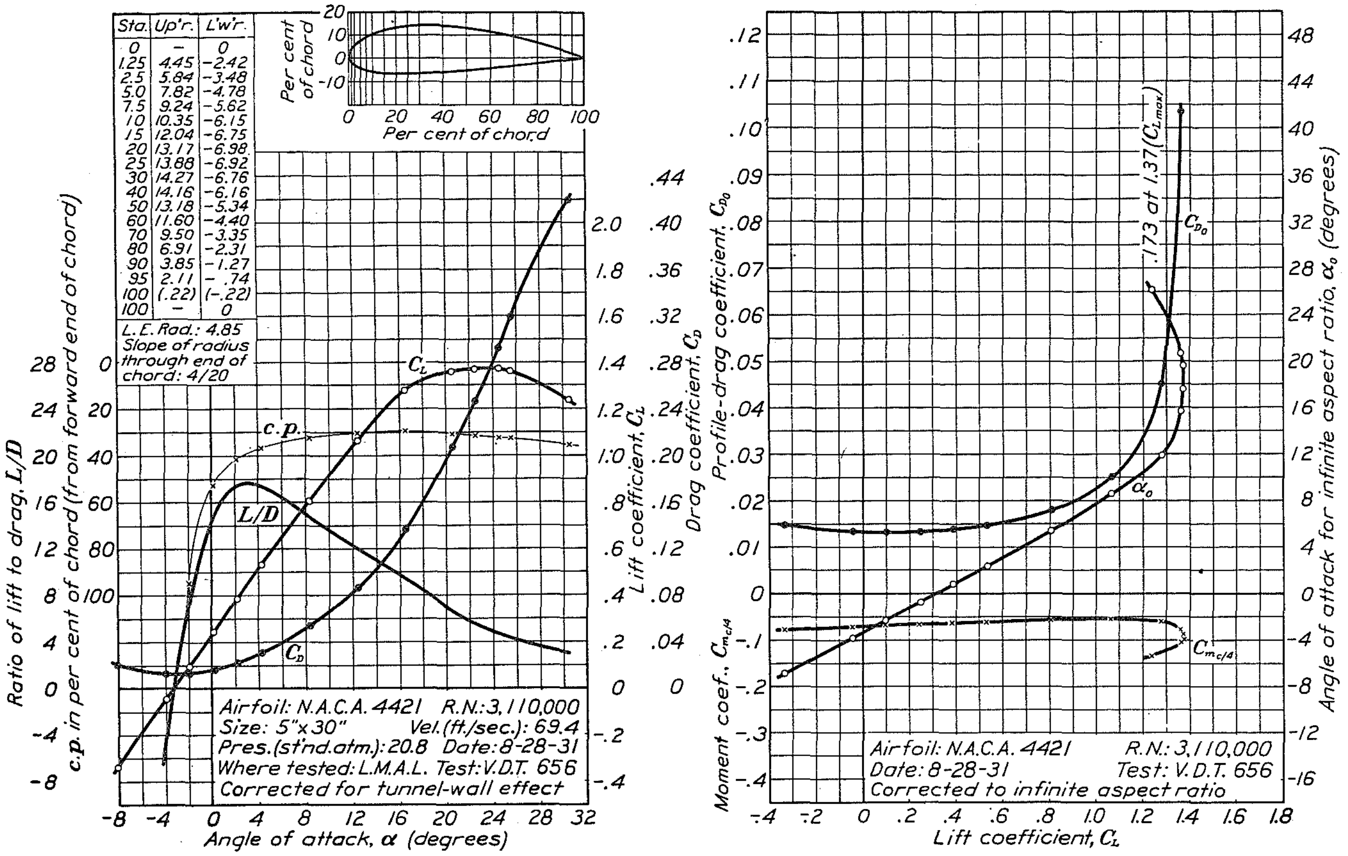
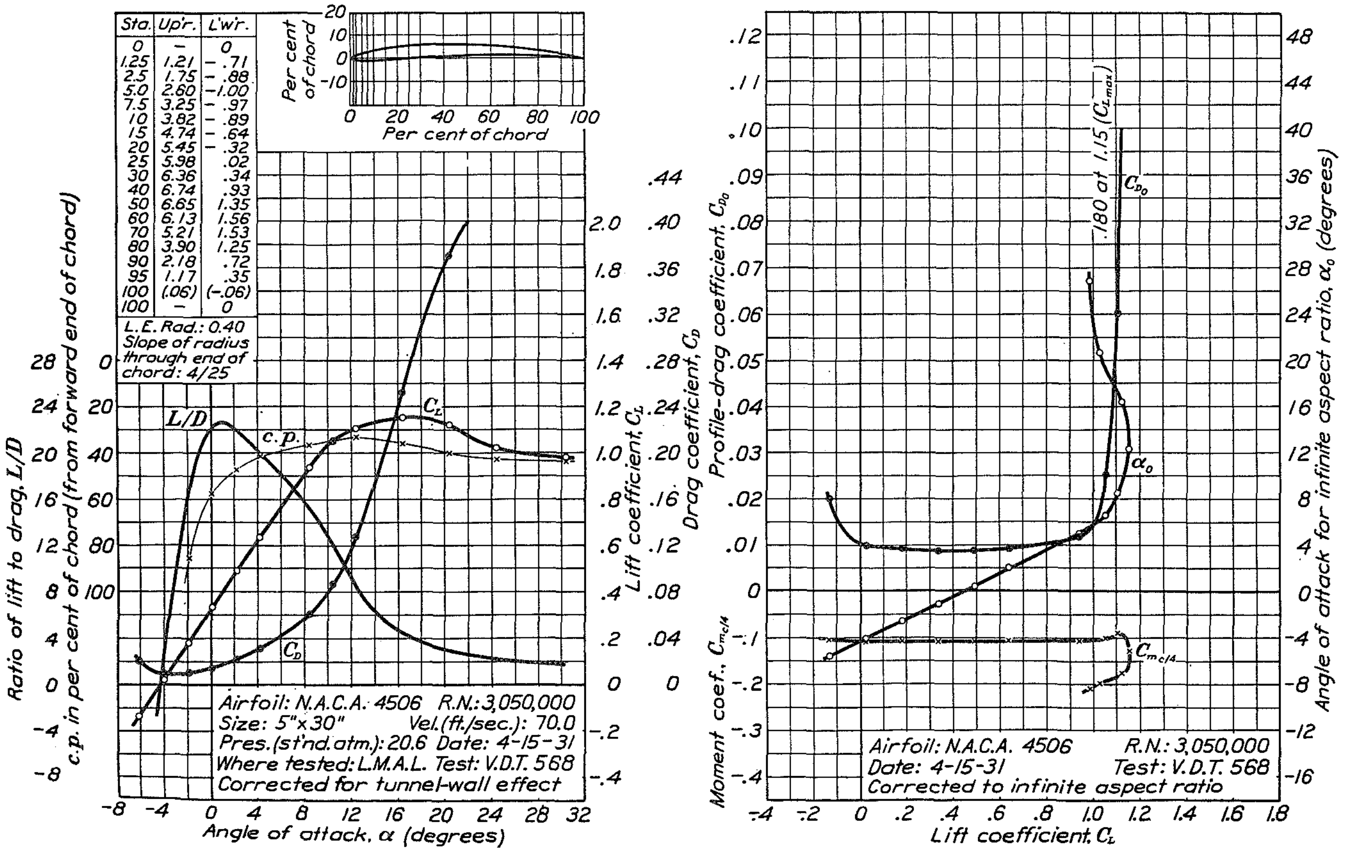


FIGURE 41.—N.A.C.A. 4418 airfoil.



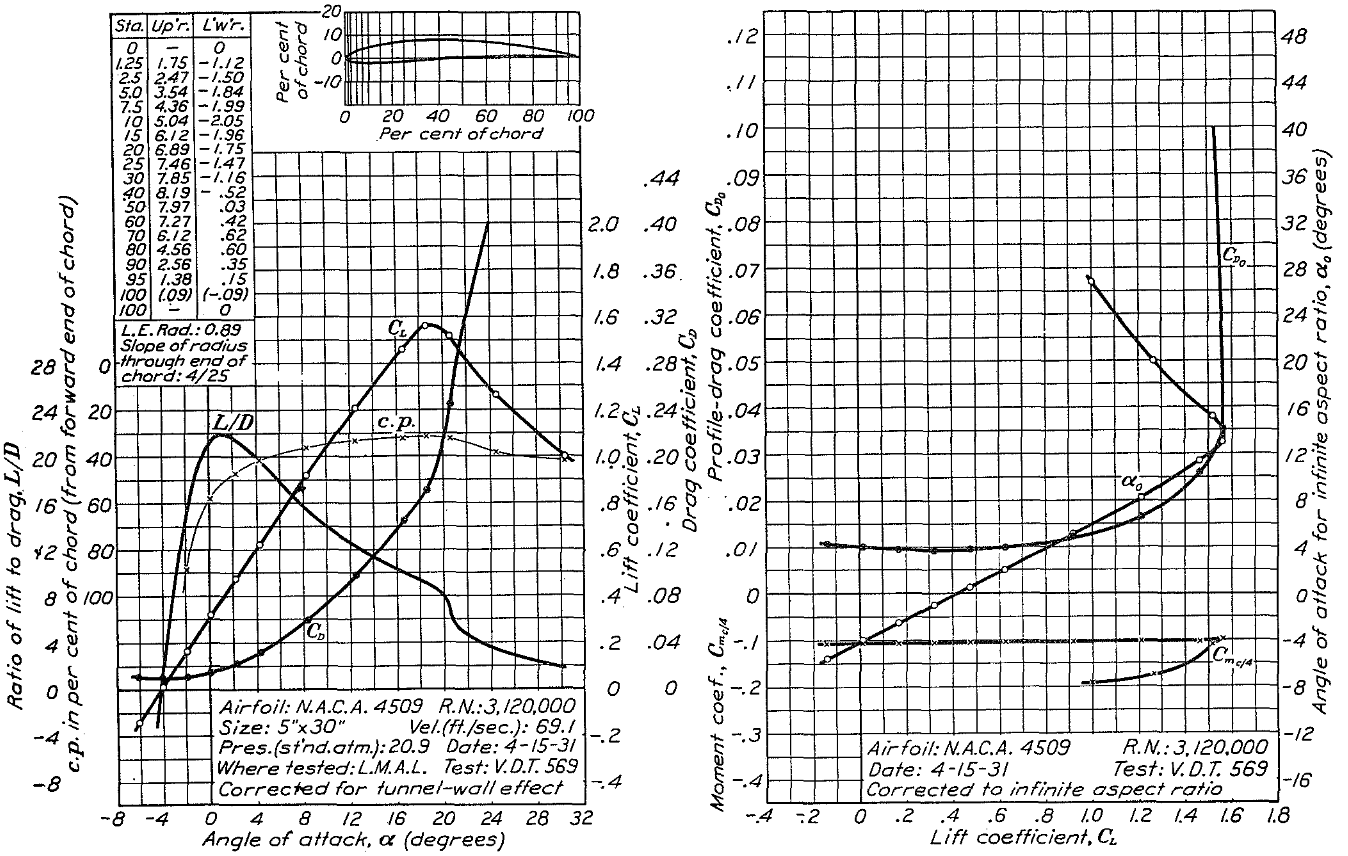
Sta.	Up'r.	L'w'r.
0	–	0
1.25	4.45	–2.42
2.5	5.84	–3.48
5.0	7.82	–4.78
7.5	9.24	–5.62
10	10.35	–6.15
15	12.04	–6.75
20	13.17	–6.98
25	13.88	–6.92
30	14.27	–6.76
40	14.16	–6.16
50	13.18	–5.34
60	11.60	–4.40
70	9.50	–3.35
80	6.91	–2.31
90	3.85	–1.27
95	2.11	– .74
100	(.22)	(–.22)
100	–	0

FIGURE 42.—N.A.C.A. 4421 airfoil.



Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.21	– .71
2.5	1.75	– .88
5.0	2.60	–1.00
7.5	3.25	– .97
10	3.82	– .89
15	4.74	– .64
20	5.45	– .32
25	5.98	.02
30	6.36	.34
40	6.74	.93
50	6.65	1.35
60	6.13	1.56
70	5.21	1.53
80	3.90	1.25
90	2.18	.72
95	1.17	.35
100	(.06)	(–.06)
100	–	0

FIGURE 43.—N.A.C.A. 4506 airfoil.



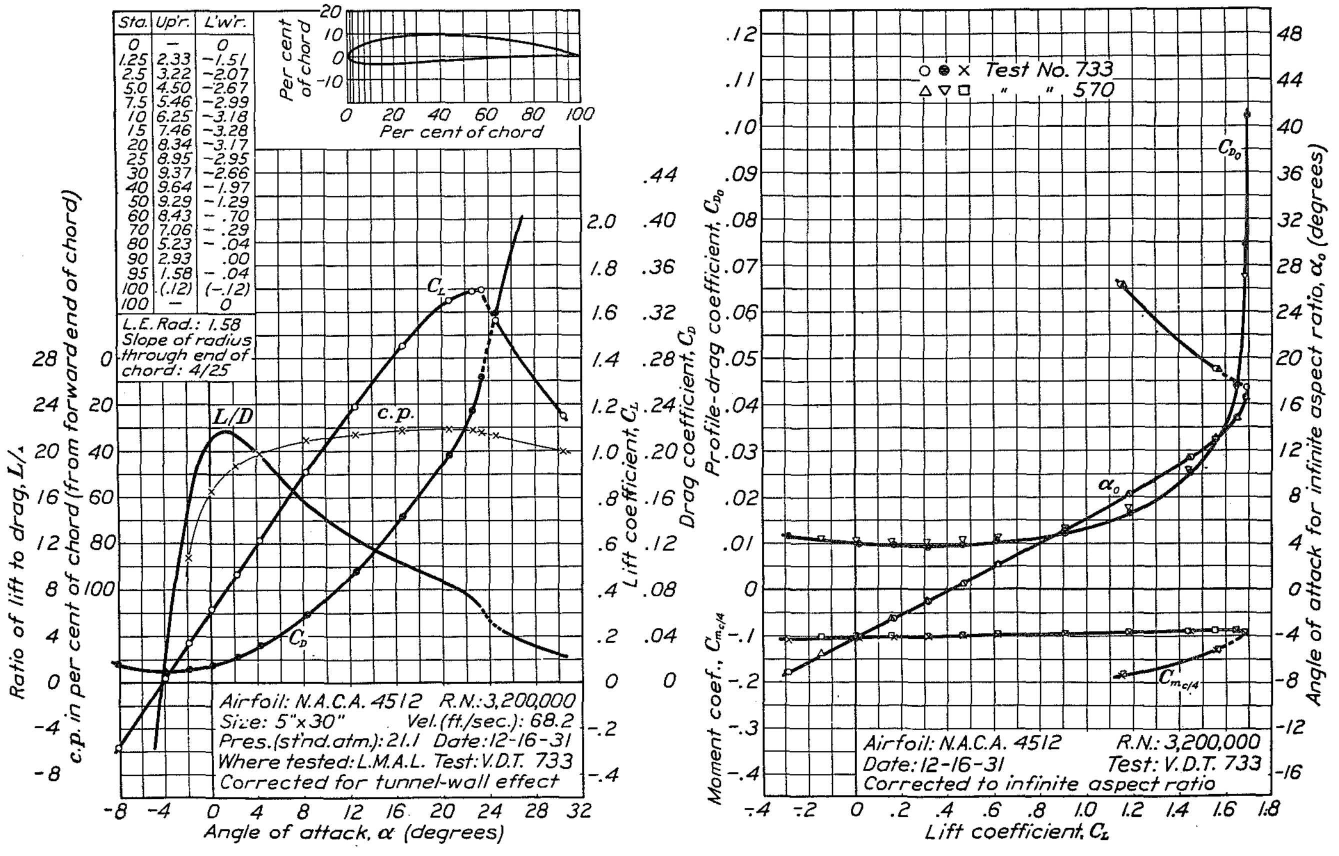
Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.75	–1.12
2.5	2.47	–1.50
5.0	3.54	–1.84
7.5	4.36	–1.99
10	5.04	–2.05
15	6.12	–1.96
20	6.89	–1.75
25	7.46	–1.47
30	7.85	–1.16
40	8.19	– .52
50	7.97	.03
60	7.27	.42
70	6.12	.62
80	4.56	.60
90	2.56	.35
95	1.38	.15
100	(.09)	(–.09)
100	–	0

L.E. Rad.: 0.89
Slope of radius through end of chord: 4/25

Airfoil: N.A.C.A. 4509 R.N.: 3,120,000
Size: 5"x30" Vel. (ft./sec.): 69.1
Pres. (st'nd. atm.): 20.9 Date: 4-15-31
Where tested: L.M.A.L. Test: V.D.T. 569
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4509 R.N.: 3,120,000
Date: 4-15-31 Test: V.D.T. 569
Corrected to infinite aspect ratio

FIGURE 44.—N.A.C.A. 4509 airfoil.



Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.33	–1.51
2.5	3.22	–2.07
5.0	4.50	–2.67
7.5	5.46	–2.99
10	6.25	–3.18
15	7.46	–3.28
20	8.34	–3.17
25	8.95	–2.95
30	9.37	–2.66
40	9.64	–1.97
50	9.29	–1.29
60	8.43	– .70
70	7.06	– .29
80	5.23	– .04
90	2.93	.00
95	1.58	– .04
100	(.12)	(–.12)
100	–	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 4/25

Airfoil: N.A.C.A. 4512 R.N.: 3,200,000
Size: 5"x30" Vel. (ft./sec.): 68.2
Pres. (st'nd. atm.): 21.1 Date: 12-16-31
Where tested: L.M.A.L. Test: V.D.T. 733
Corrected for tunnel-wall effect

○ ● × Test No. 733
△ ▽ □ " " 570

Airfoil: N.A.C.A. 4512 R.N.: 3,200,000
Date: 12-16-31 Test: V.D.T. 733
Corrected to infinite aspect ratio

FIGURE 45.—N.A.C.A. 4512 airfoil.

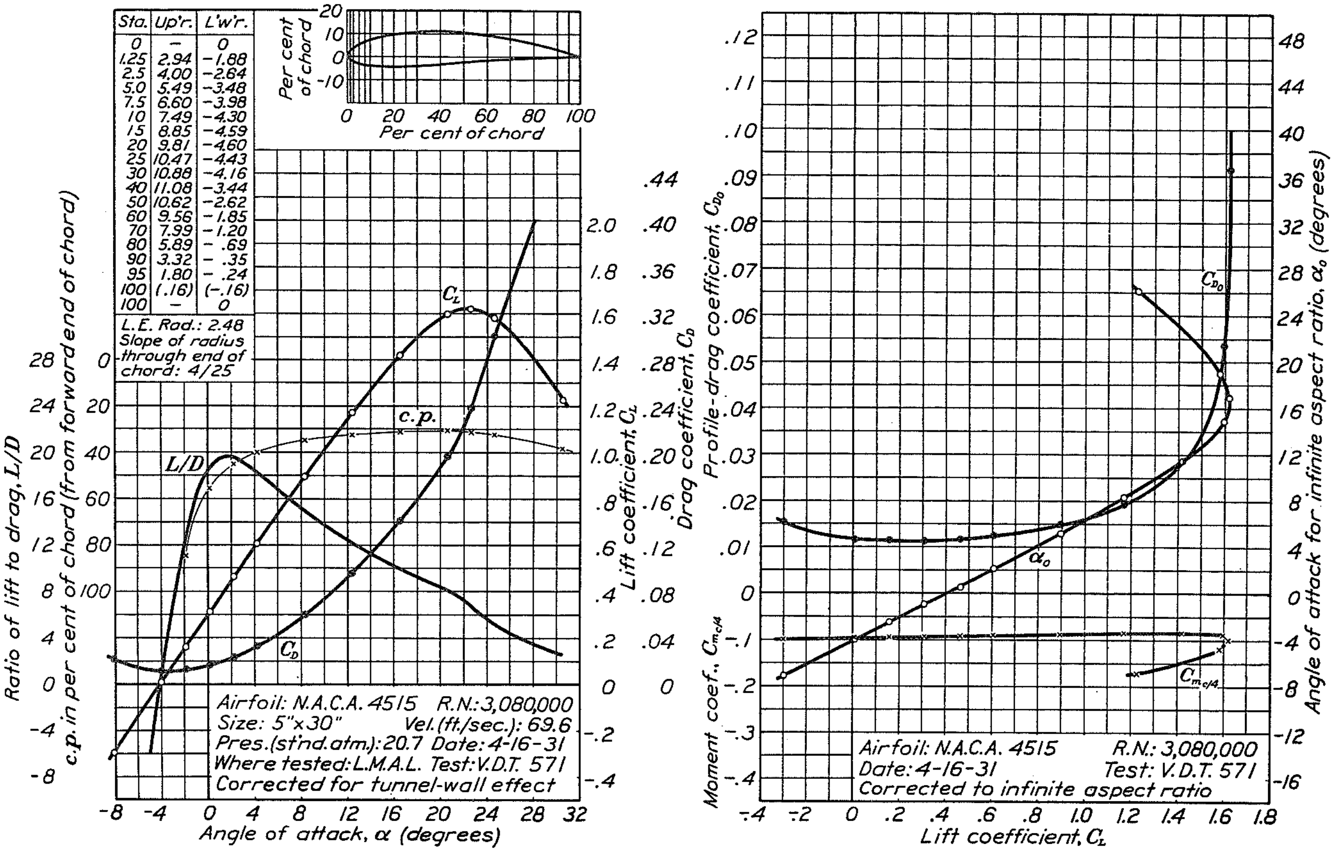


FIGURE 46.—N.A.C.A. 4515 airfoil.

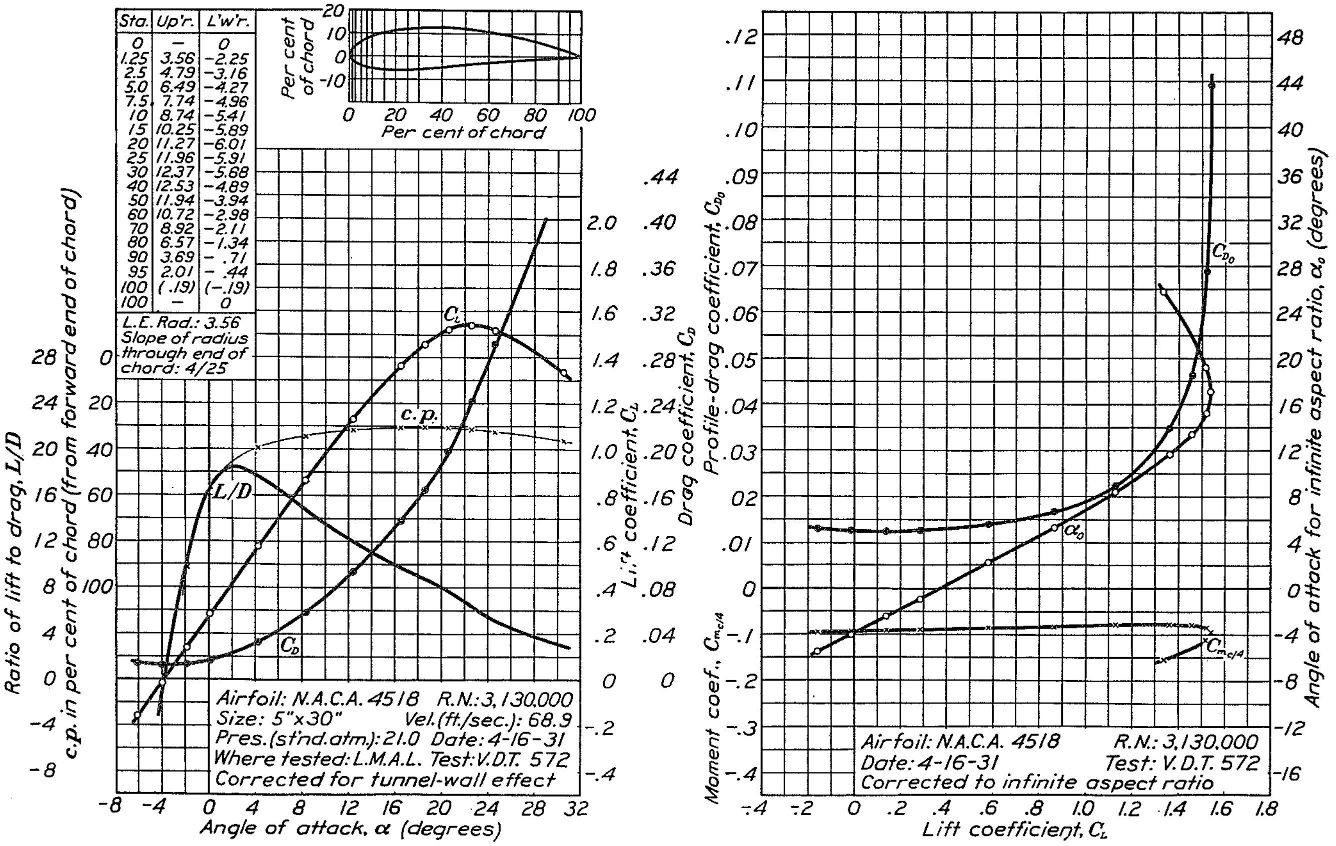
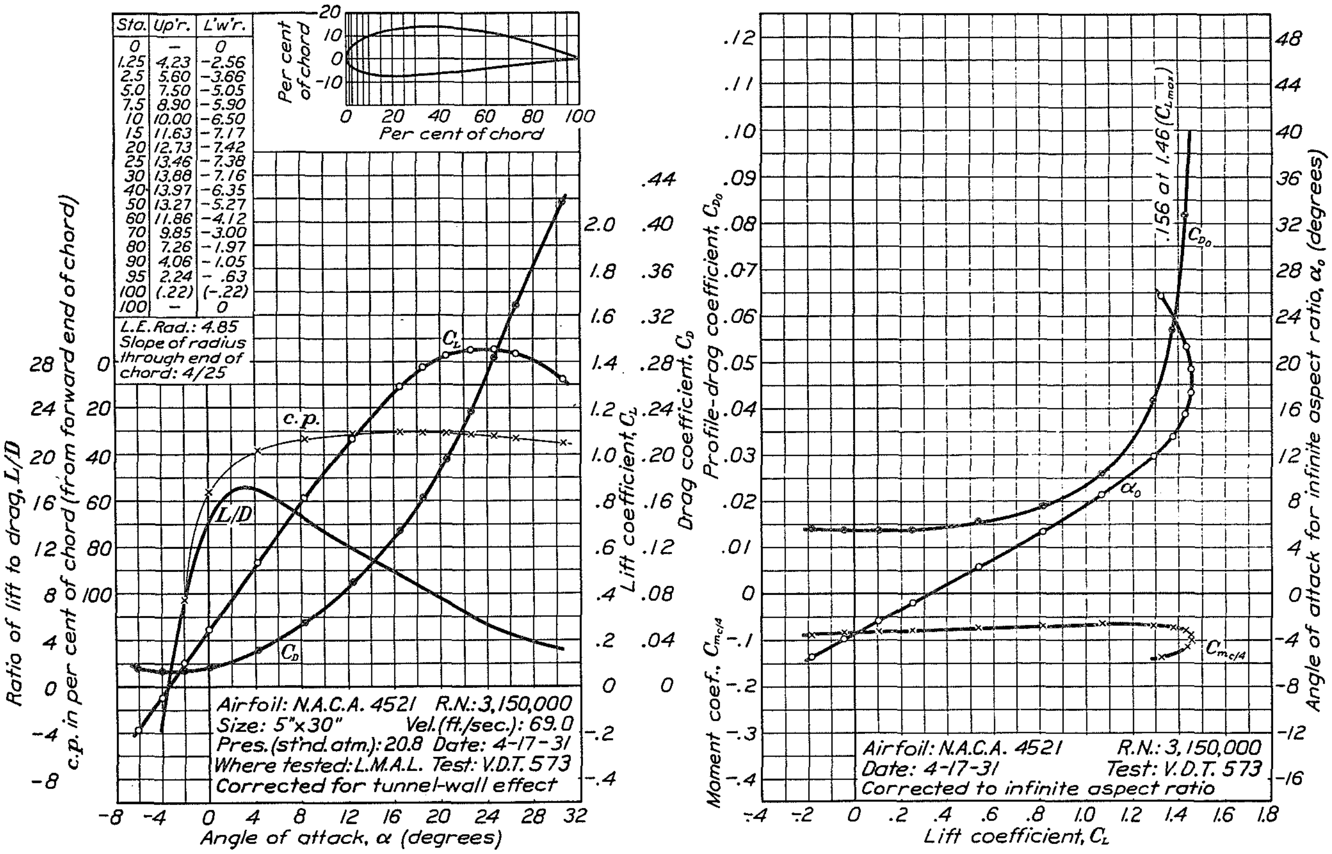


FIGURE 47.—N.A.C.A. 4518 airfoil.



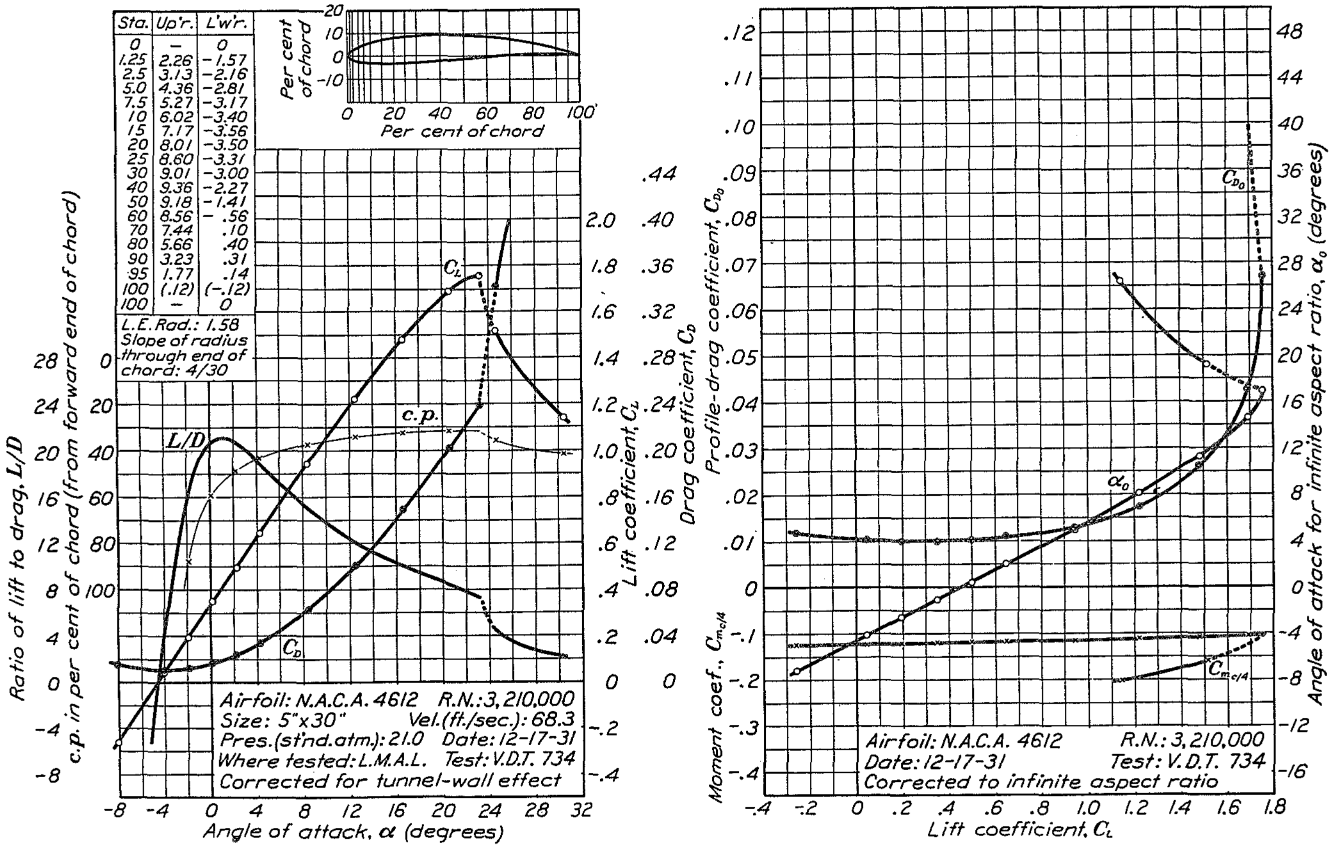
Sta.	Up'r.	L'w'r.
0	—	0
1.25	4.23	−2.56
2.5	5.60	−3.66
5.0	7.50	−5.05
7.5	8.90	−5.90
10	10.00	−6.50
15	11.63	−7.17
20	12.73	−7.42
25	13.46	−7.38
30	13.88	−7.16
40	13.97	−6.35
50	13.27	−5.27
60	11.86	−4.12
70	9.85	−3.00
80	7.26	−1.97
90	4.06	−1.05
95	2.24	− .63
100	(.22)	(−.22)
100	—	0

L.E. Rad.: 4.85
Slope of radius through end of chord: 4/25

Airfoil: N.A.C.A. 4521 R.N.: 3,150,000
Size: 5"x30" Vel. (ft./sec.): 69.0
Pres. (st'nd. atm.): 20.8 Date: 4-17-31
Where tested: L.M.A.L. Test: V.D.T. 573
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4521 R.N.: 3,150,000
Date: 4-17-31 Test: V.D.T. 573
Corrected to infinite aspect ratio

FIGURE 48.—N.A.C.A. 4521 airfoil.



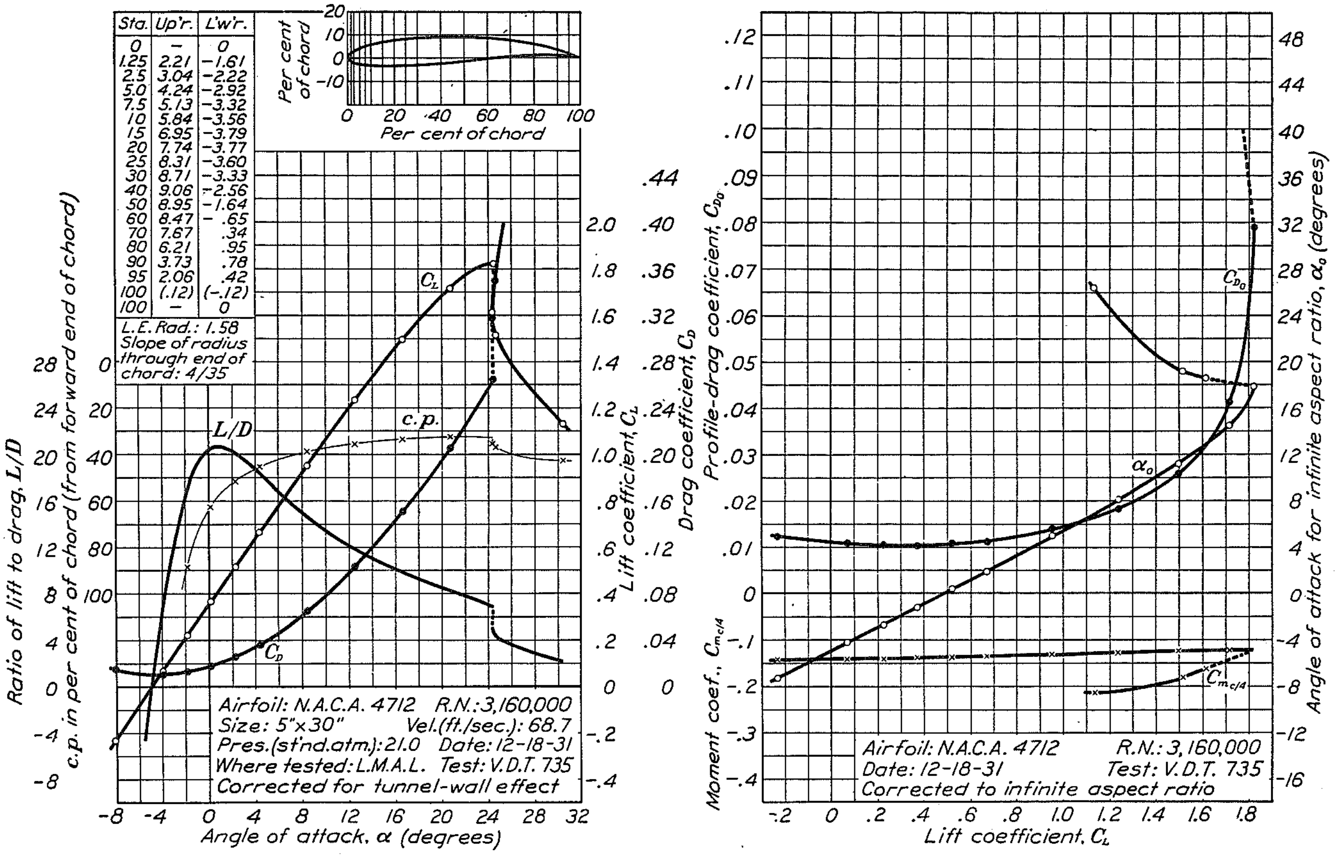
Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.26	−1.57
2.5	3.13	−2.16
5.0	4.36	−2.81
7.5	5.27	−3.17
10	6.02	−3.40
15	7.17	−3.56
20	8.01	−3.50
25	8.60	−3.31
30	9.01	−3.00
40	9.36	−2.27
50	9.18	−1.41
60	8.56	− .56
70	7.44	.10
80	5.66	.40
90	3.23	.31
95	1.77	.14
100	(.12)	(−.12)
100	—	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 4/30

Airfoil: N.A.C.A. 4612 R.N.: 3,210,000
Size: 5"x30" Vel. (ft./sec.): 68.3
Pres. (st'nd. atm.): 21.0 Date: 12-17-31
Where tested: L.M.A.L. Test: V.D.T. 734
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4612 R.N.: 3,210,000
Date: 12-17-31 Test: V.D.T. 734
Corrected to infinite aspect ratio

FIGURE 49.—N.A.C.A. 4612 airfoil.



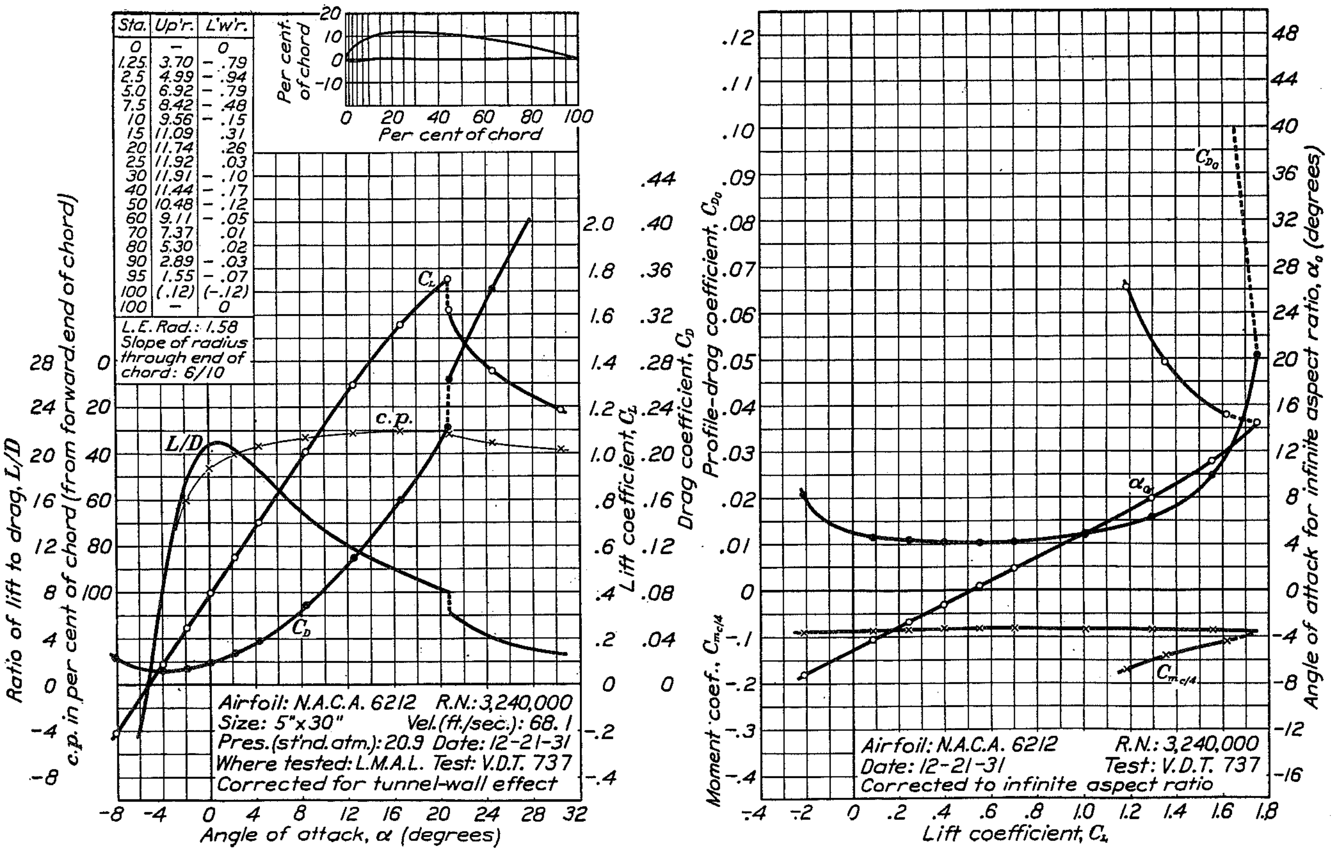
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.21	–1.61
2.5	3.04	–2.22
5.0	4.24	–2.92
7.5	5.13	–3.32
10	5.84	–3.56
15	6.95	–3.79
20	7.74	–3.77
25	8.31	–3.60
30	8.71	–3.33
40	9.06	–2.56
50	8.95	–1.64
60	8.47	– .65
70	7.67	.34
80	6.21	.95
90	3.73	.78
95	2.06	.42
100	(.12)	(–.12)
100	–	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 4/35

Airfoil: N.A.C.A. 4712 R.N.: 3,160,000
Size: 5"×30" Vel.(ft./sec.): 68.7
Pres.(st'nd.atm.): 21.0 Date: 12-18-31
Where tested: L.M.A.L. Test: V.D.T. 735
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 4712 R.N.: 3,160,000
Date: 12-18-31 Test: V.D.T. 735
Corrected to infinite aspect ratio

FIGURE 50.—N.A.C.A. 4712 airfoil.



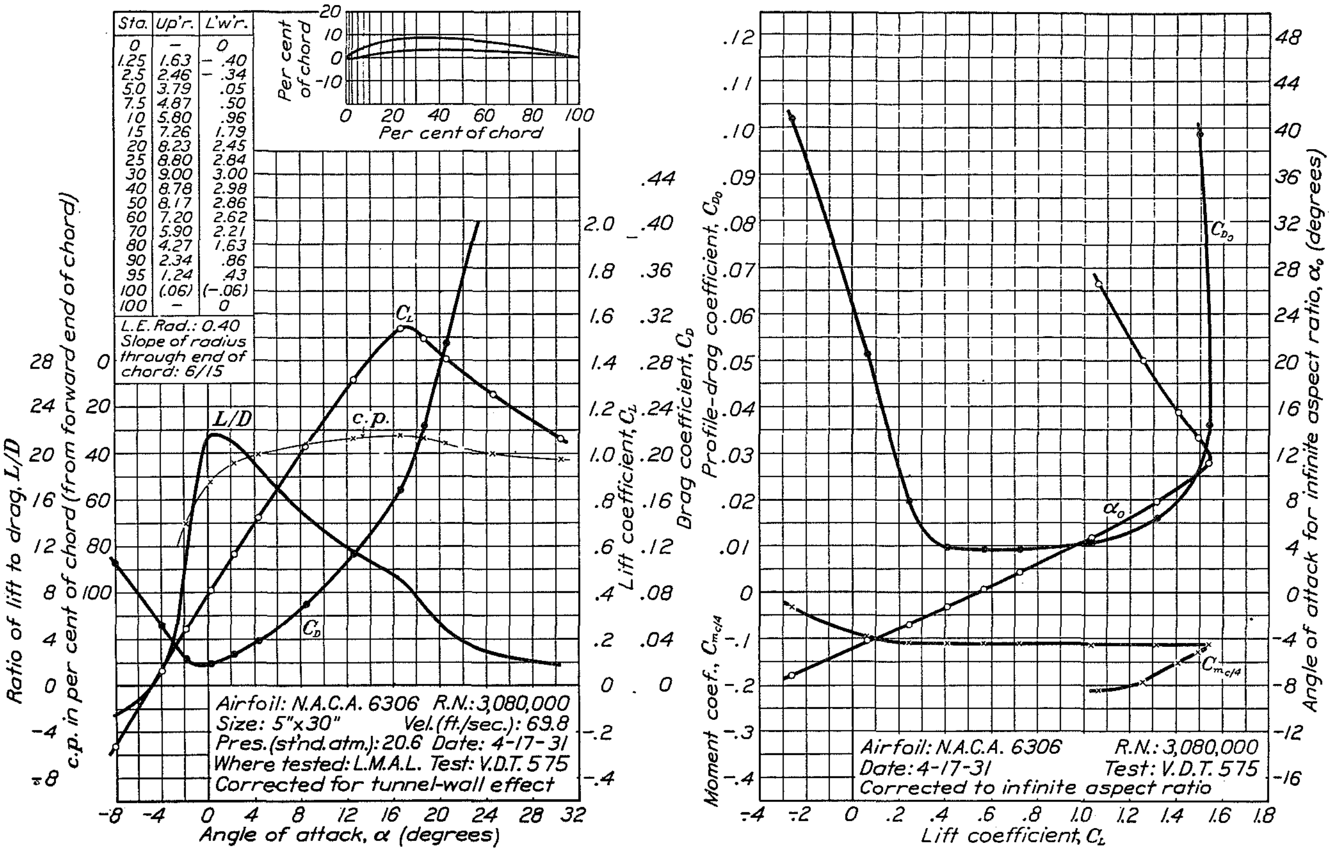
Sta.	Up'r.	L'w'r.
0	–	0
1.25	3.70	– .79
2.5	4.99	– .94
5.0	6.92	– .79
7.5	8.42	– .48
10	9.56	– .15
15	11.09	.31
20	11.74	.26
25	11.92	.03
30	11.91	– .10
40	11.44	– .17
50	10.48	– .12
60	9.11	– .05
70	7.37	.01
80	5.30	.02
90	2.89	– .03
95	1.55	– .07
100	(.12)	(–.12)
100	–	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 6/10

Airfoil: N.A.C.A. 6212 R.N.: 3,240,000
Size: 5"×30" Vel.(ft./sec.): 68.1
Pres.(st'nd.atm.): 20.9 Date: 12-21-31
Where tested: L.M.A.L. Test: V.D.T. 737
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6212 R.N.: 3,240,000
Date: 12-21-31 Test: V.D.T. 737
Corrected to infinite aspect ratio

FIGURE 51.—N.A.C.A. 6212 airfoil.



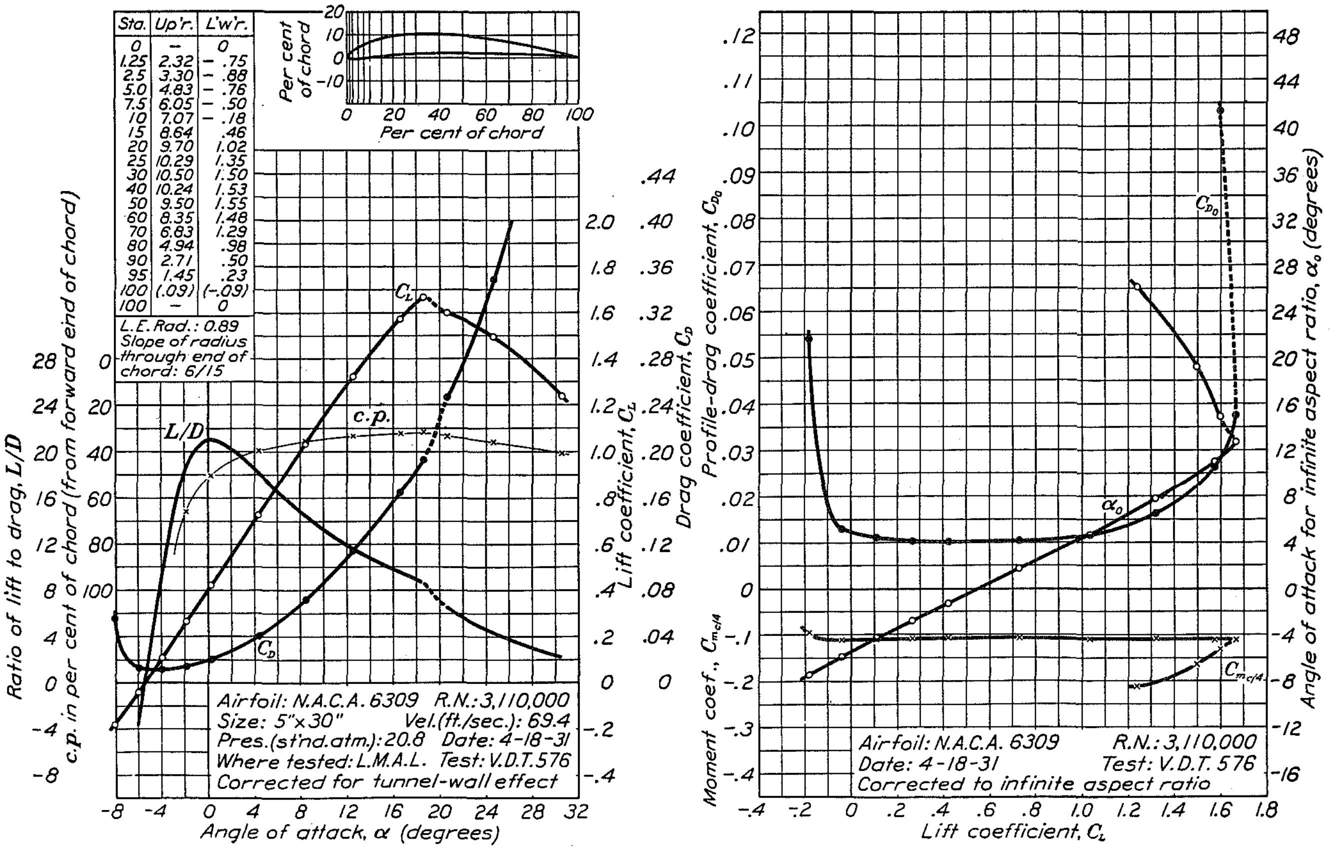
Sta.	Up'r.	L'w'r.
0	–	0
1.25	1.63	– .40
2.5	2.46	– .34
5.0	3.79	.05
7.5	4.87	.50
10	5.80	.96
15	7.26	1.79
20	8.23	2.45
25	8.80	2.84
30	9.00	3.00
40	8.78	2.98
50	8.17	2.86
60	7.20	2.62
70	5.90	2.21
80	4.27	1.63
90	2.34	.86
95	1.24	.43
100	(.06)	(–.06)
100	–	0

L.E. Rad.: 0.40
Slope of radius through end of chord: 6/15

Airfoil: N.A.C.A. 6306 R.N.: 3,080,000
Size: 5"x30" Vel. (ft./sec.): 69.8
Pres. (st'nd. atm.): 20.6 Date: 4-17-31
Where tested: L.M.A.L. Test: V.D.T. 575
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6306 R.N.: 3,080,000
Date: 4-17-31 Test: V.D.T. 575
Corrected to infinite aspect ratio

FIGURE 52.—N.A.C.A. 6306 airfoil.



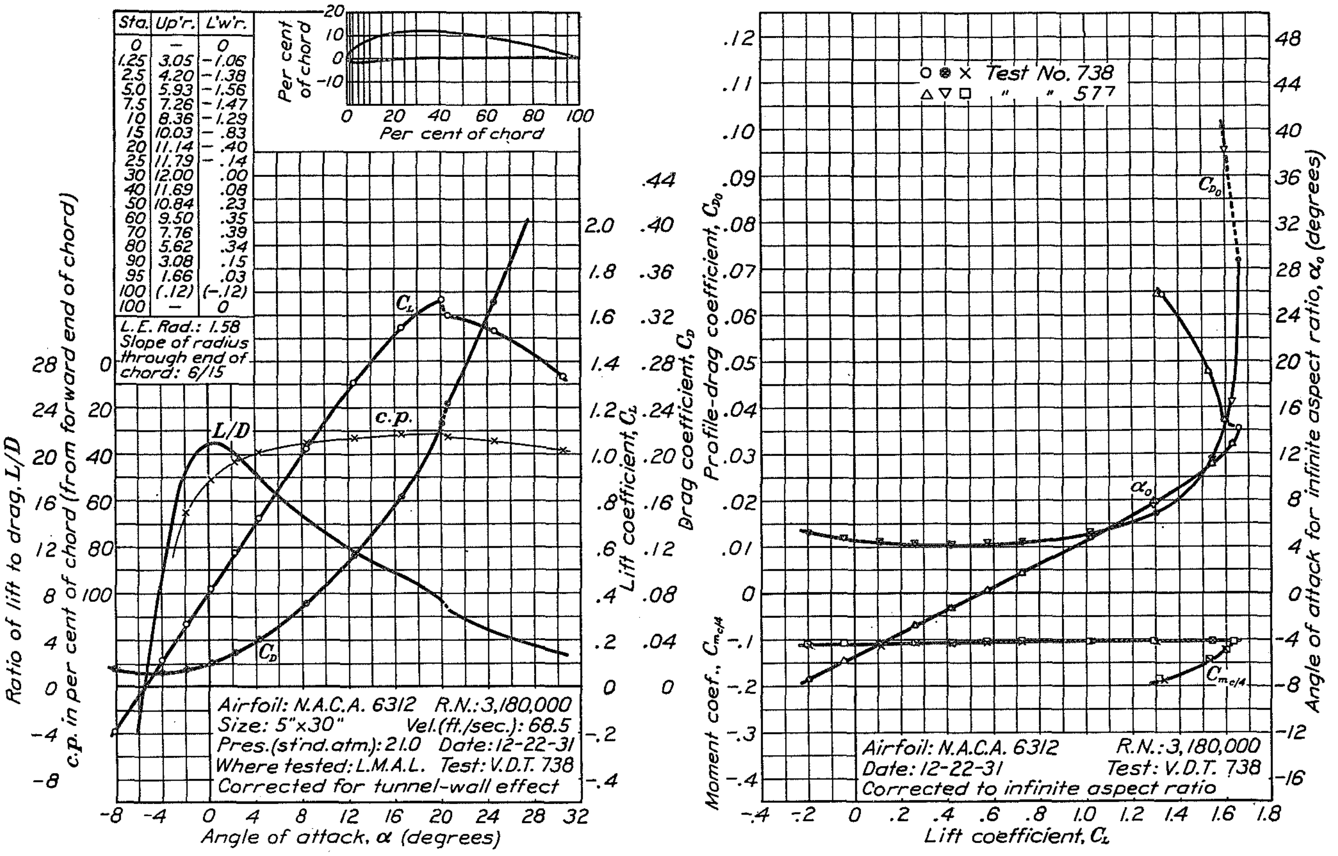
Sta.	Up'r.	L'w'r.
0	–	0
1.25	2.32	– .75
2.5	3.30	– .88
5.0	4.83	– .76
7.5	6.05	– .50
10	7.07	– .18
15	8.64	.46
20	9.70	1.02
25	10.29	1.35
30	10.50	1.50
40	10.24	1.53
50	9.50	1.55
60	8.35	1.48
70	6.83	1.29
80	4.94	.98
90	2.71	.50
95	1.45	.23
100	(.09)	(–.09)
100	–	0

L.E. Rad.: 0.89
Slope of radius through end of chord: 6/15

Airfoil: N.A.C.A. 6309 R.N.: 3,110,000
Size: 5"x30" Vel. (ft./sec.): 69.4
Pres. (st'nd. atm.): 20.8 Date: 4-18-31
Where tested: L.M.A.L. Test: V.D.T. 576
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6309 R.N.: 3,110,000
Date: 4-18-31 Test: V.D.T. 576
Corrected to infinite aspect ratio

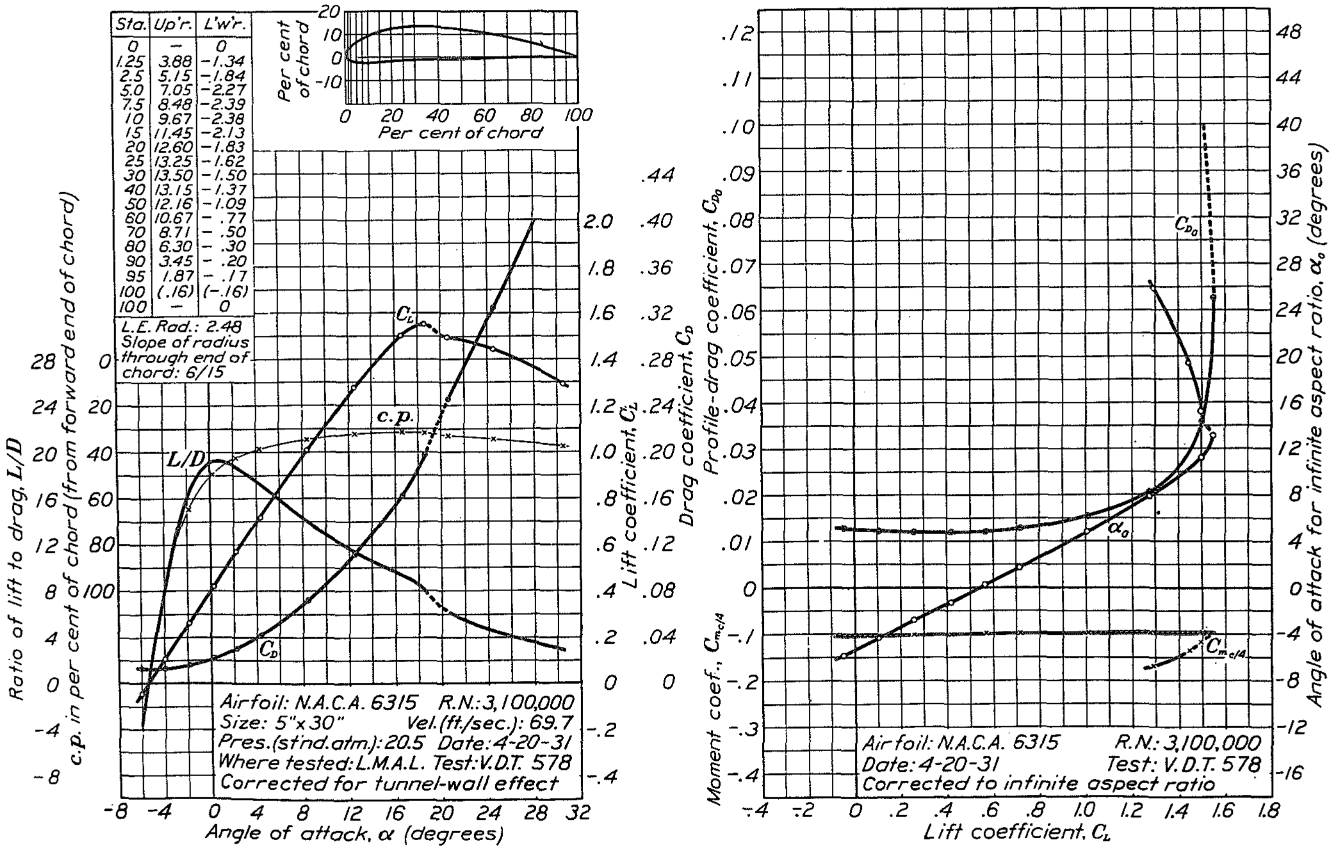
FIGURE 53.—N.A.C.A. 6309 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.05	−1.06
2.5	4.20	−1.38
5.0	5.93	−1.56
7.5	7.26	−1.47
10	8.36	−1.29
15	10.03	− .83
20	11.14	− .40
25	11.79	− .14
30	12.00	.00
40	11.69	.08
50	10.84	.23
60	9.50	.35
70	7.76	.39
80	5.62	.34
90	3.08	.15
95	1.66	.03
100	(.12)	(−.12)
100	—	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 6/15

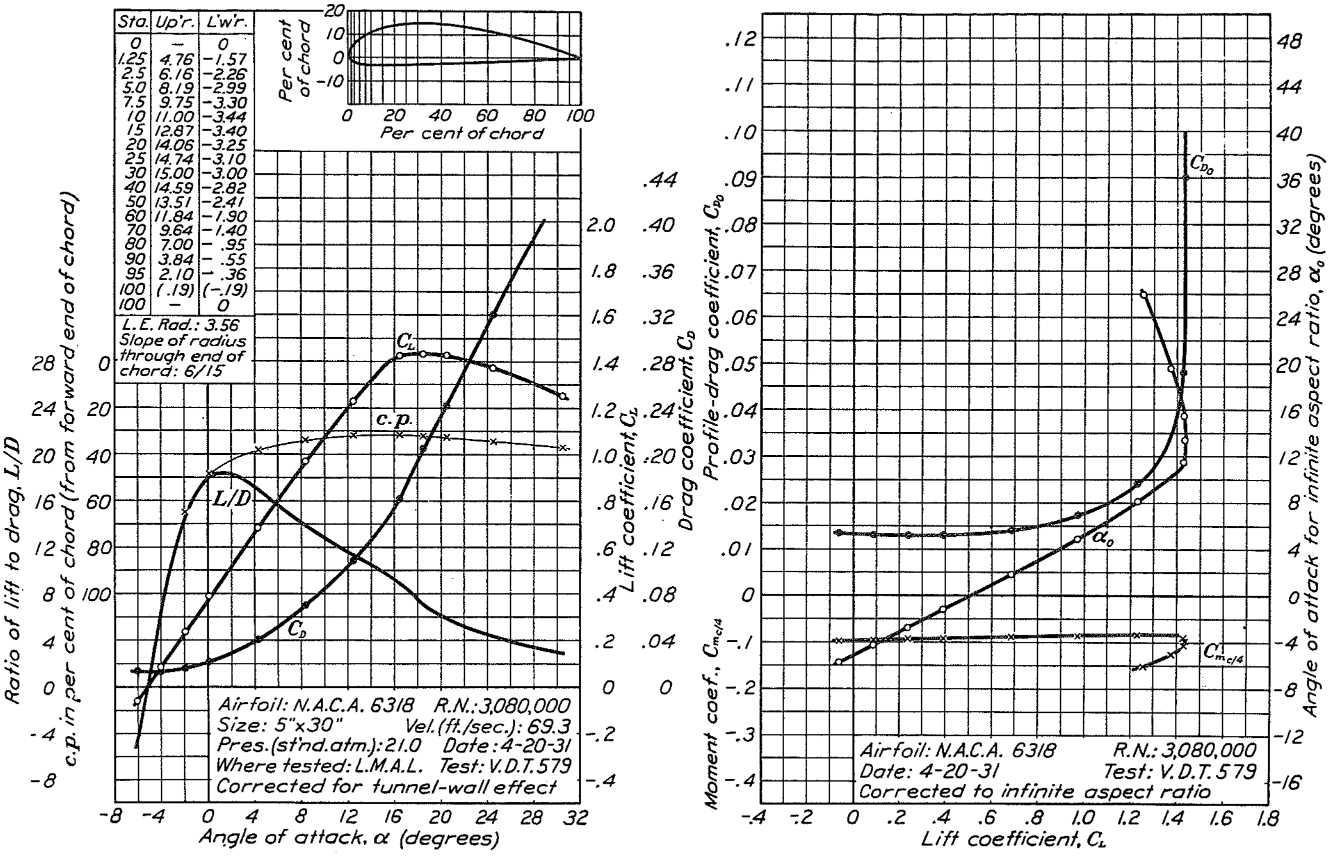
FIGURE 54.—N.A.C.A. 6312 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.88	−1.34
2.5	5.15	−1.84
5.0	7.05	−2.27
7.5	8.48	−2.39
10	9.67	−2.38
15	11.45	−2.13
20	12.60	−1.83
25	13.25	−1.62
30	13.50	−1.50
40	13.15	−1.37
50	12.16	−1.09
60	10.67	− .77
70	8.71	− .50
80	6.30	− .30
90	3.45	− .20
95	1.87	− .17
100	(.16)	(−.16)
100	—	0

L.E. Rad.: 2.48
Slope of radius through end of chord: 6/15

FIGURE 55.—N.A.C.A. 6315 airfoil.



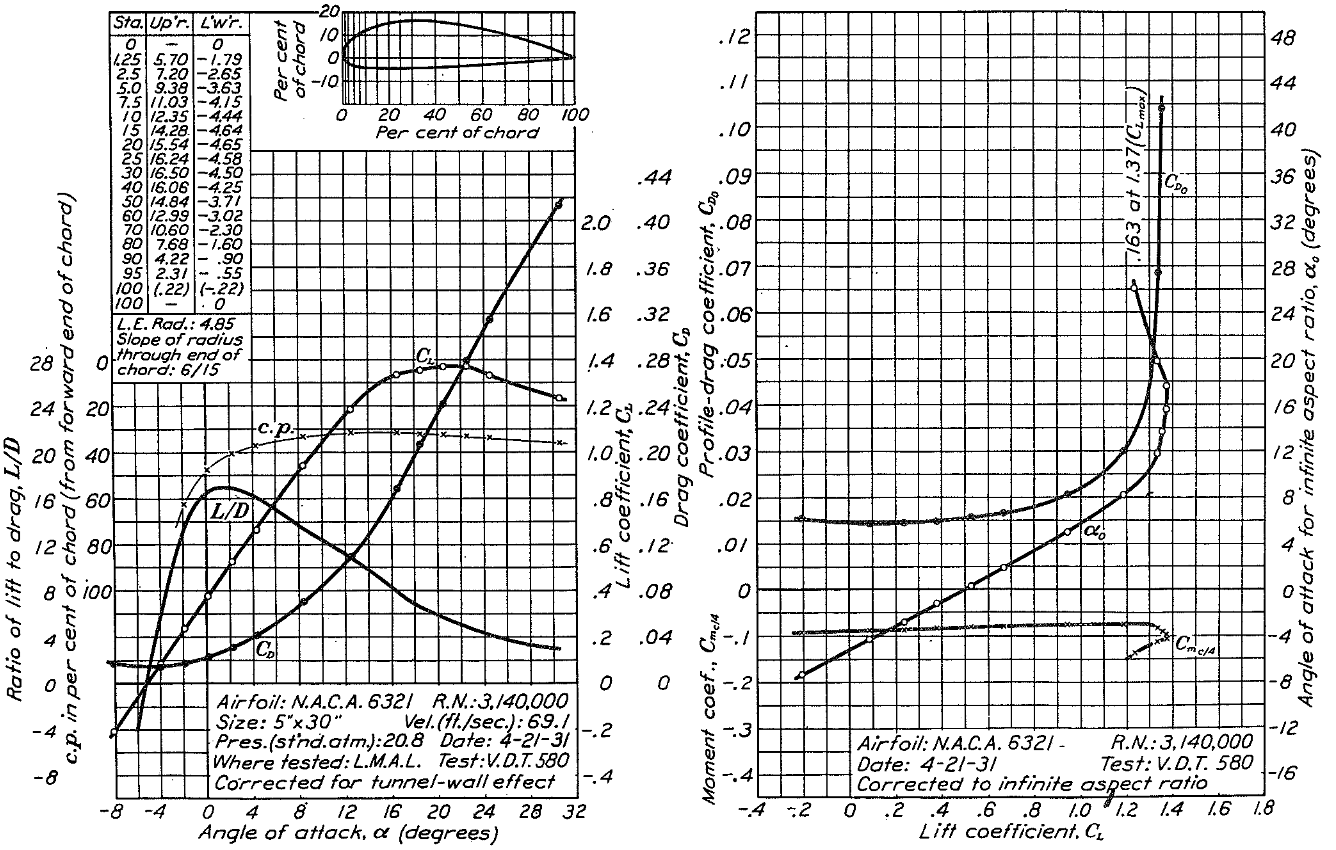
Sta.	Up'r.	L'w'r.
0	—	0
1.25	4.76	−1.57
2.5	6.16	−2.26
5.0	8.19	−2.99
7.5	9.75	−3.30
10	11.00	−3.44
15	12.87	−3.40
20	14.06	−3.25
25	14.74	−3.10
30	15.00	−3.00
40	14.59	−2.82
50	13.51	−2.41
60	11.84	−1.90
70	9.64	−1.40
80	7.00	− .95
90	3.84	− .55
95	2.10	− .36
100	(.19)	(−.19)
100	—	0

L. E. Rad.: 3.56
Slope of radius through end of chord: 6/15

Airfoil: N.A.C.A. 6318 R.N.: 3,080,000
Size: 5"x30" Vel. (ft./sec.): 69.3
Pres. (st'nd. atm.): 21.0 Date: 4-20-31
Where tested: L.M.A.L. Test: V.D.T. 579
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6318 R.N.: 3,080,000
Date: 4-20-31 Test: V.D.T. 579
Corrected to infinite aspect ratio

FIGURE 56.—N.A.C.A. 6318 airfoil.



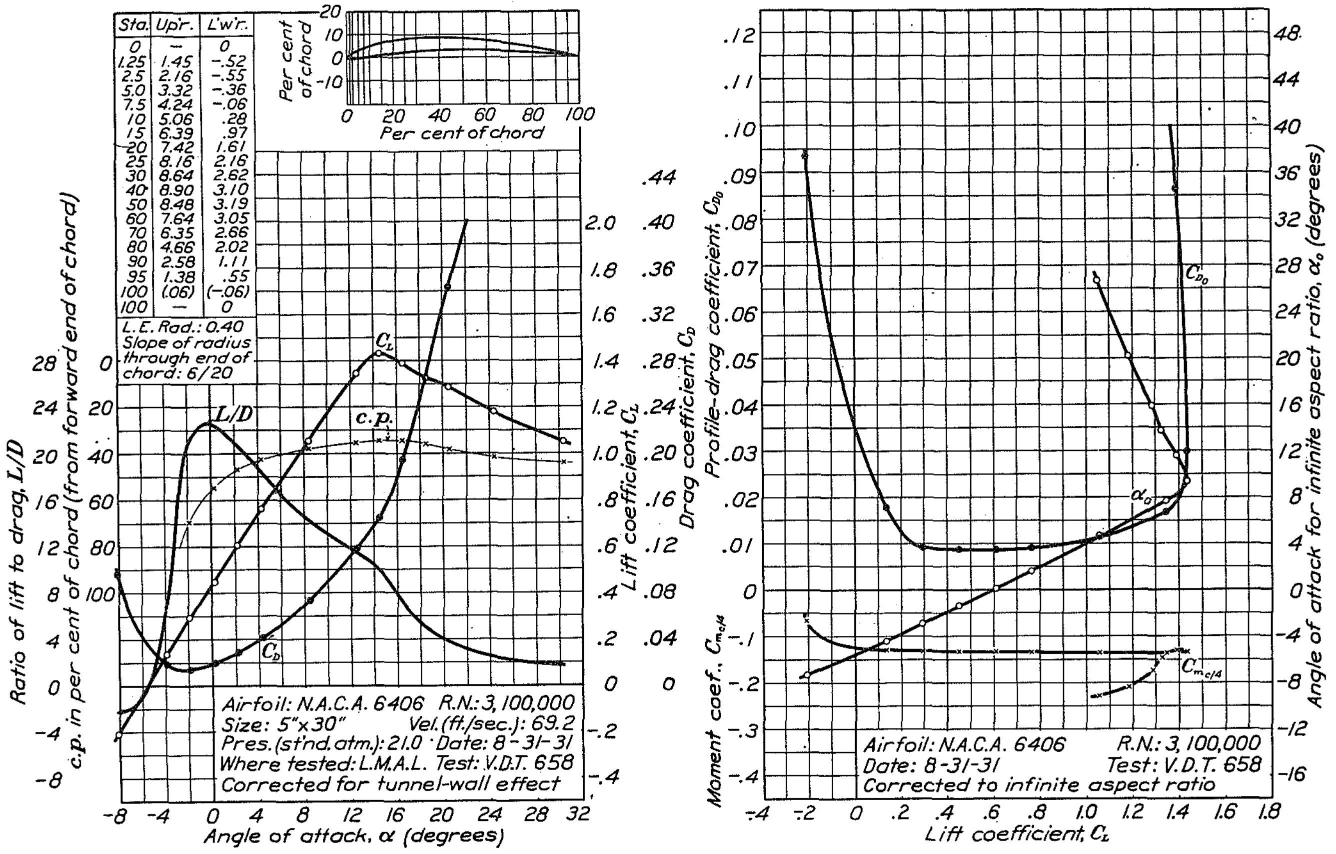
Sta.	Up'r.	L'w'r.
0	—	0
1.25	5.70	−1.79
2.5	7.20	−2.65
5.0	9.38	−3.63
7.5	11.03	−4.15
10	12.35	−4.44
15	14.28	−4.64
20	15.54	−4.65
25	16.24	−4.58
30	16.50	−4.50
40	16.06	−4.25
50	14.84	−3.71
60	12.99	−3.02
70	10.60	−2.30
80	7.68	−1.60
90	4.22	− .90
95	2.31	− .55
100	(.22)	(−.22)
100	—	0

L. E. Rad.: 4.85
Slope of radius through end of chord: 6/15

Airfoil: N.A.C.A. 6321 R.N.: 3,140,000
Size: 5"x30" Vel. (ft./sec.): 69.1
Pres. (st'nd. atm.): 20.8 Date: 4-21-31
Where tested: L.M.A.L. Test: V.D.T. 580
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6321 - R.N.: 3,140,000
Date: 4-21-31 Test: V.D.T. 580
Corrected to infinite aspect ratio

FIGURE 57.—N.A.C.A. 6321 airfoil.



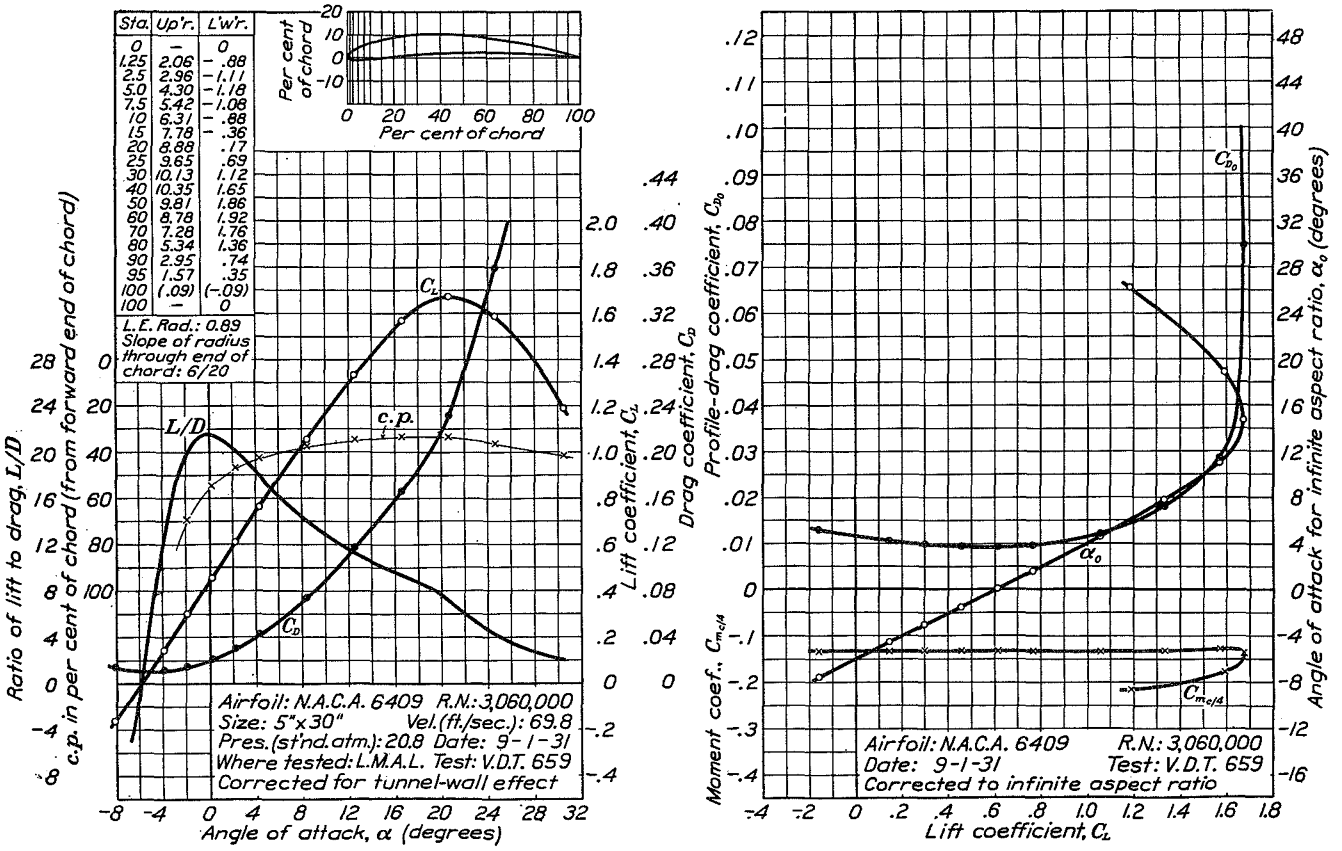
Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.45	−.52
2.5	2.16	−.55
5.0	3.32	−.36
7.5	4.24	−.06
10	5.06	.28
15	6.39	.97
20	7.42	1.61
25	8.16	2.16
30	8.64	2.62
40	8.90	3.10
50	8.48	3.19
60	7.64	3.05
70	6.35	2.66
80	4.66	2.02
90	2.58	1.11
95	1.38	.55
100	(.06)	(−.06)
100	—	0

L. E. Rad.: 0.40
Slope of radius through end of chord: 6/20

Airfoil: N.A.C.A. 6406 R.N.: 3,100,000
Size: 5"×30" Vel.(ft./sec.): 69.2
Pres.(st'nd.atm.): 21.0 Date: 8-31-31
Where tested: L.M.A.L. Test: V.D.T. 658
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6406 R.N.: 3,100,000
Date: 8-31-31 Test: V.D.T. 658
Corrected to infinite aspect ratio

FIGURE 58.—N.A.C.A. 6406 airfoil.



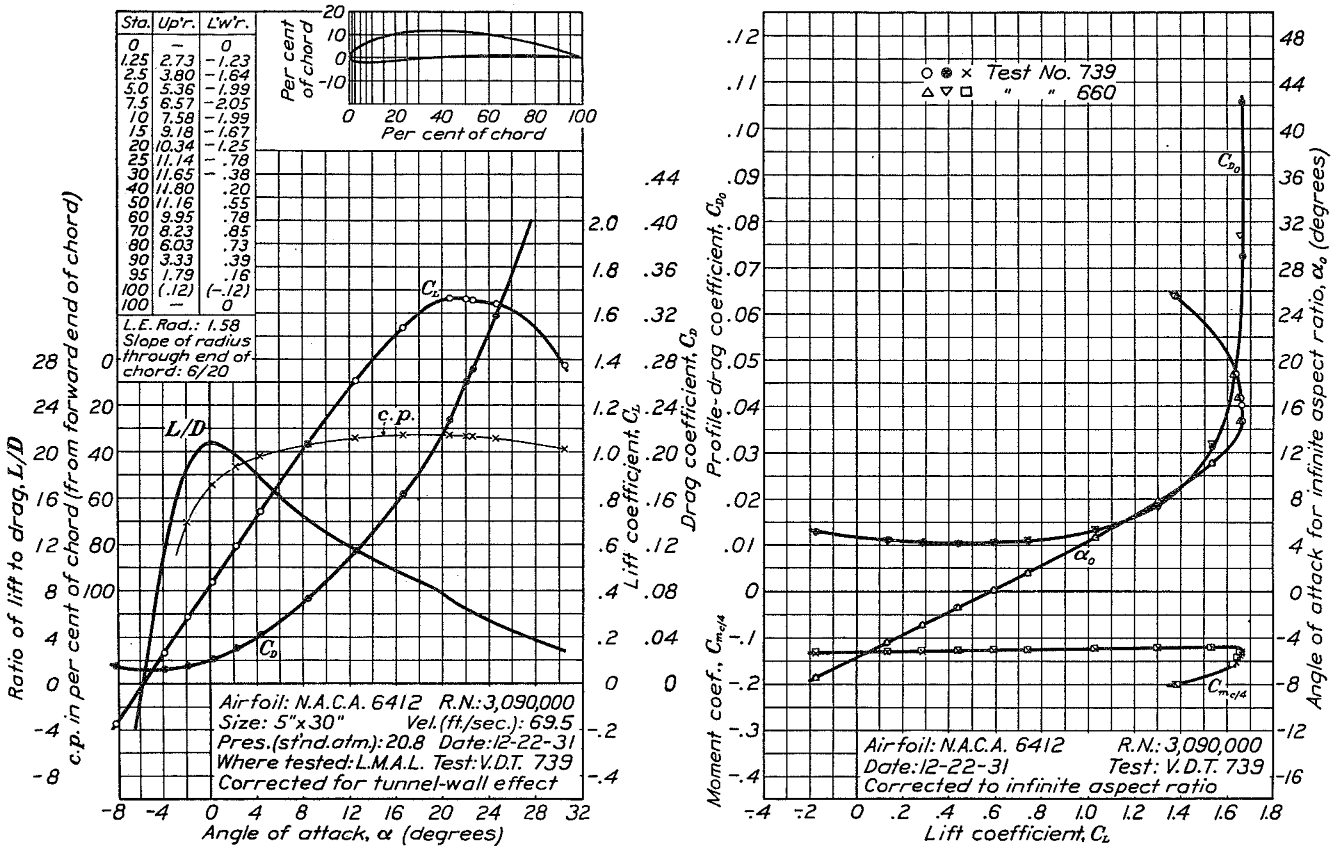
Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.06	− .88
2.5	2.96	−1.11
5.0	4.30	−1.18
7.5	5.42	−1.08
10	6.31	− .88
15	7.78	− .36
20	8.88	.17
25	9.65	.69
30	10.13	1.12
40	10.35	1.65
50	9.81	1.86
60	8.78	1.92
70	7.28	1.76
80	5.34	1.36
90	2.95	.74
95	1.57	.35
100	(.09)	(−.09)
100	—	0

L. E. Rad.: 0.89
Slope of radius through end of chord: 6/20

Airfoil: N.A.C.A. 6409 R.N.: 3,060,000
Size: 5"×30" Vel.(ft./sec.): 69.8
Pres.(st'nd.atm.): 20.8 Date: 9-1-31
Where tested: L.M.A.L. Test: V.D.T. 659
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6409 R.N.: 3,060,000
Date: 9-1-31 Test: V.D.T. 659
Corrected to infinite aspect ratio

FIGURE 59.—N.A.C.A. 6409 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.73	−1.23
2.5	3.80	−1.64
5.0	5.36	−1.99
7.5	6.57	−2.05
10	7.58	−1.99
15	9.18	−1.67
20	10.34	−1.25
25	11.14	− .78
30	11.65	− .38
40	11.80	.20
50	11.16	.55
60	9.95	.78
70	8.23	.85
80	6.03	.73
90	3.33	.39
95	1.79	.16
100	(.12)	(−.12)
100	—	0

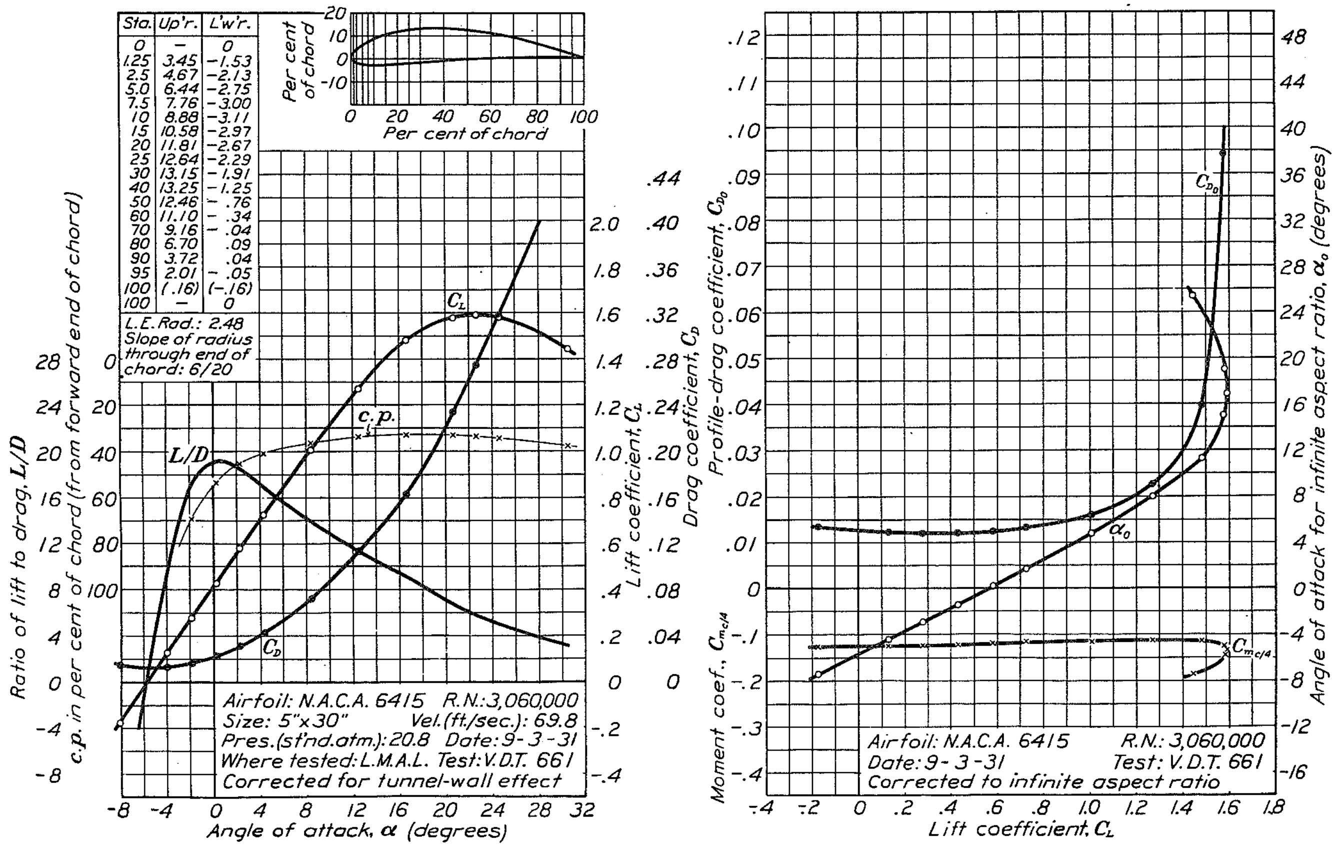
L.E. Rad.: 1.58
Slope of radius through end of chord: 6/20

Airfoil: N.A.C.A. 6412 R.N.: 3,090,000
Size: 5"x30" Vel.(ft./sec.): 69.5
Pres.(st'nd.atm.): 20.8 Date: 12-22-31
Where tested: L.M.A.L. Test: V.D.T. 739
Corrected for tunnel-wall effect

○ ● × Test No. 739
△ ▽ □ " " 660

Airfoil: N.A.C.A. 6412 R.N.: 3,090,000
Date: 12-22-31 Test: V.D.T. 739
Corrected to infinite aspect ratio

FIGURE 60.—N.A.C.A. 6412 airfoil.



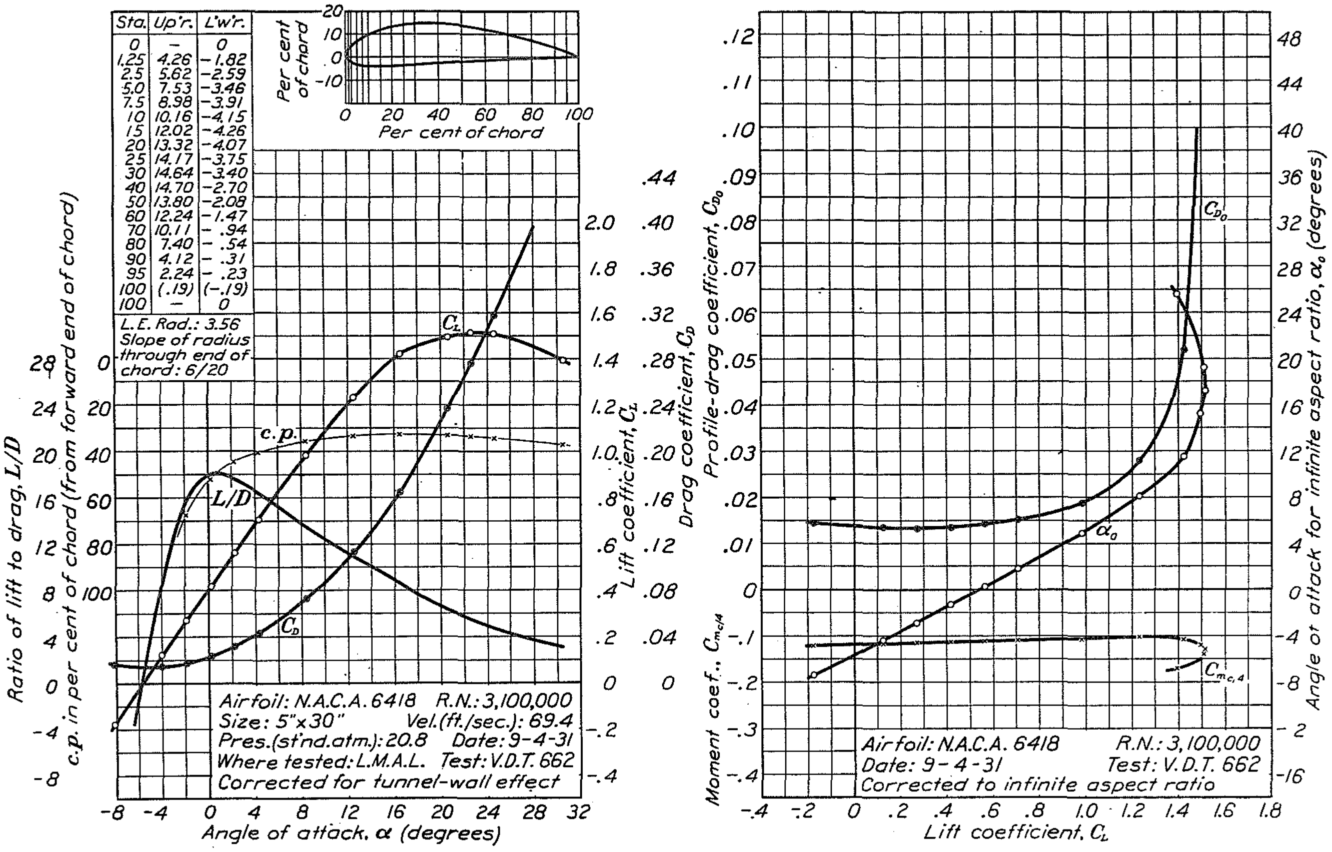
Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.45	−1.53
2.5	4.67	−2.13
5.0	6.44	−2.75
7.5	7.76	−3.00
10	8.88	−3.11
15	10.58	−2.97
20	11.81	−2.67
25	12.64	−2.29
30	13.15	−1.91
40	13.25	−1.25
50	12.46	− .76
60	11.10	− .34
70	9.16	− .04
80	6.70	.09
90	3.72	.04
95	2.01	− .05
100	(.16)	(−.16)
100	—	0

L.E. Rad.: 2.48
Slope of radius through end of chord: 6/20

Airfoil: N.A.C.A. 6415 R.N.: 3,060,000
Size: 5"x30" Vel.(ft./sec.): 69.8
Pres.(st'nd.atm.): 20.8 Date: 9-3-31
Where tested: L.M.A.L. Test: V.D.T. 661
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6415 R.N.: 3,060,000
Date: 9-3-31 Test: V.D.T. 661
Corrected to infinite aspect ratio

FIGURE 61.—N.A.C.A. 6415 airfoil.



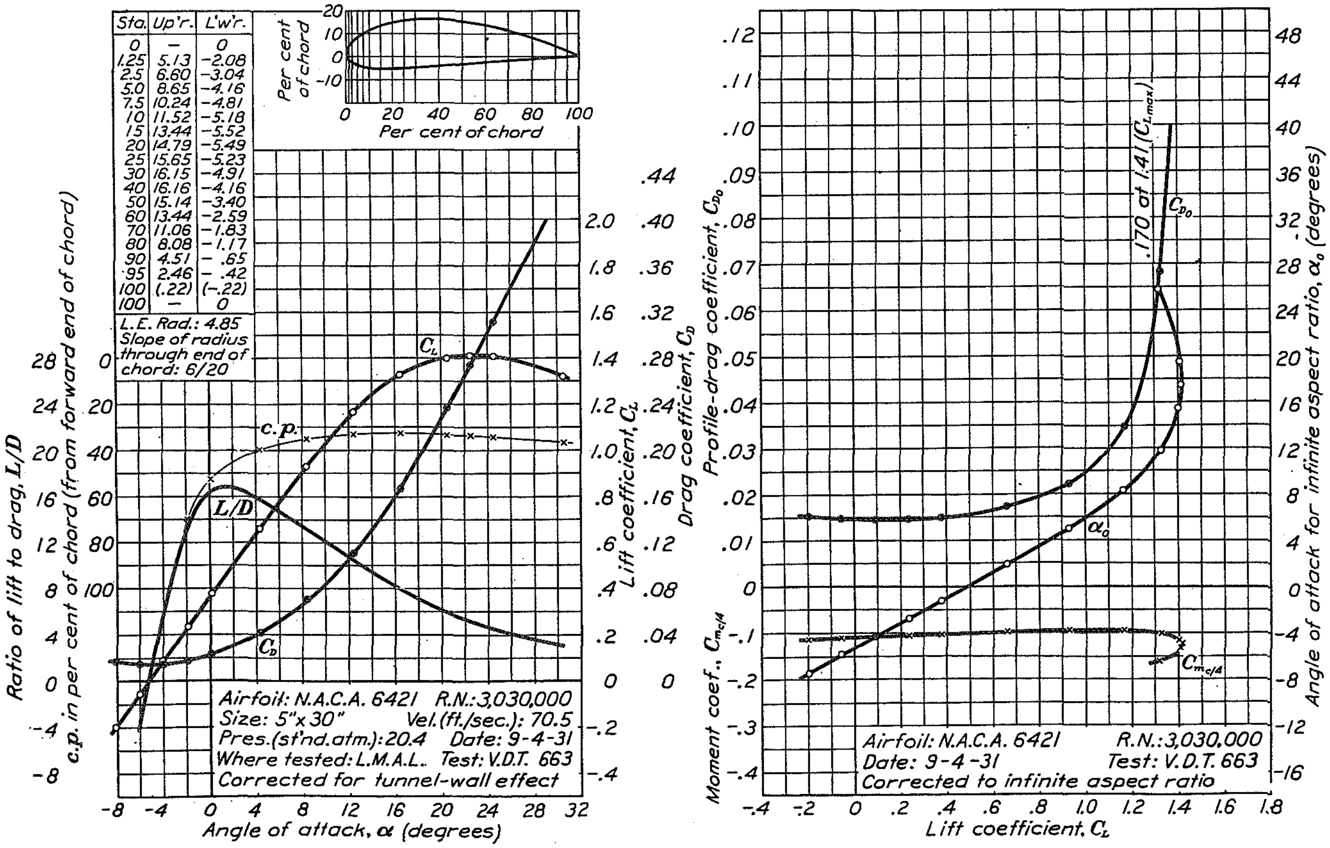
Sta.	Up'r.	L'w'r.
0	—	0
1.25	4.26	-1.82
2.5	5.62	-2.59
5.0	7.53	-3.46
7.5	8.98	-3.91
10	10.16	-4.15
15	12.02	-4.26
20	13.32	-4.07
25	14.17	-3.75
30	14.64	-3.40
40	14.70	-2.70
50	13.80	-2.08
60	12.24	-1.47
70	10.11	- .94
80	7.40	- .54
90	4.12	- .31
95	2.24	- .23
100	(.19)	(-.19)
100	—	0

L.E. Rad.: 3.56
Slope of radius through end of chord: 6/20

Airfoil: N.A.C.A. 6418 R.N.: 3,100,000
Size: 5"x30" Vel.(ft./sec.): 69.4
Pres.(st'nd.atm.): 20.8 Date: 9-4-31
Where tested: L.M.A.L. Test: V.D.T. 662
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6418 R.N.: 3,100,000
Date: 9-4-31 Test: V.D.T. 662
Corrected to infinite aspect ratio

FIGURE 62.—N.A.C.A. 6418 airfoil.



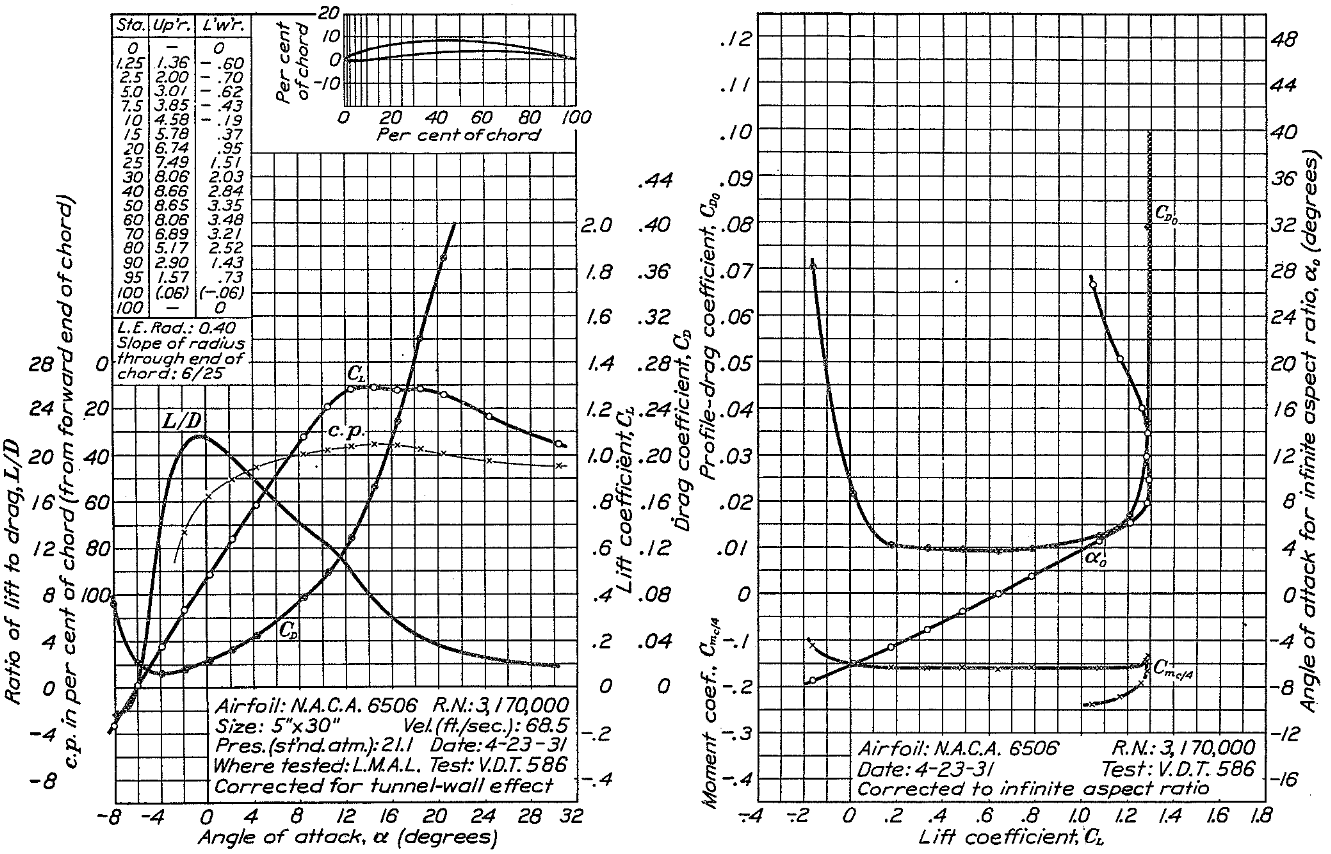
Sta.	Up'r.	L'w'r.
0	—	0
1.25	5.13	-2.08
2.5	6.60	-3.04
5.0	8.65	-4.16
7.5	10.24	-4.81
10	11.52	-5.18
15	13.44	-5.52
20	14.79	-5.49
25	15.65	-5.23
30	16.15	-4.91
40	16.16	-4.16
50	15.14	-3.40
60	13.44	-2.59
70	11.06	-1.83
80	8.08	-1.17
90	4.51	- .65
95	2.46	- .42
100	(.22)	(-.22)
100	—	0

L.E. Rad.: 4.85
Slope of radius through end of chord: 6/20

Airfoil: N.A.C.A. 6421 R.N.: 3,030,000
Size: 5"x30" Vel.(ft./sec.): 70.5
Pres.(st'nd.atm.): 20.4 Date: 9-4-31
Where tested: L.M.A.L. Test: V.D.T. 663
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6421 R.N.: 3,030,000
Date: 9-4-31 Test: V.D.T. 663
Corrected to infinite aspect ratio

FIGURE 63.—N.A.C.A. 6421 airfoil.



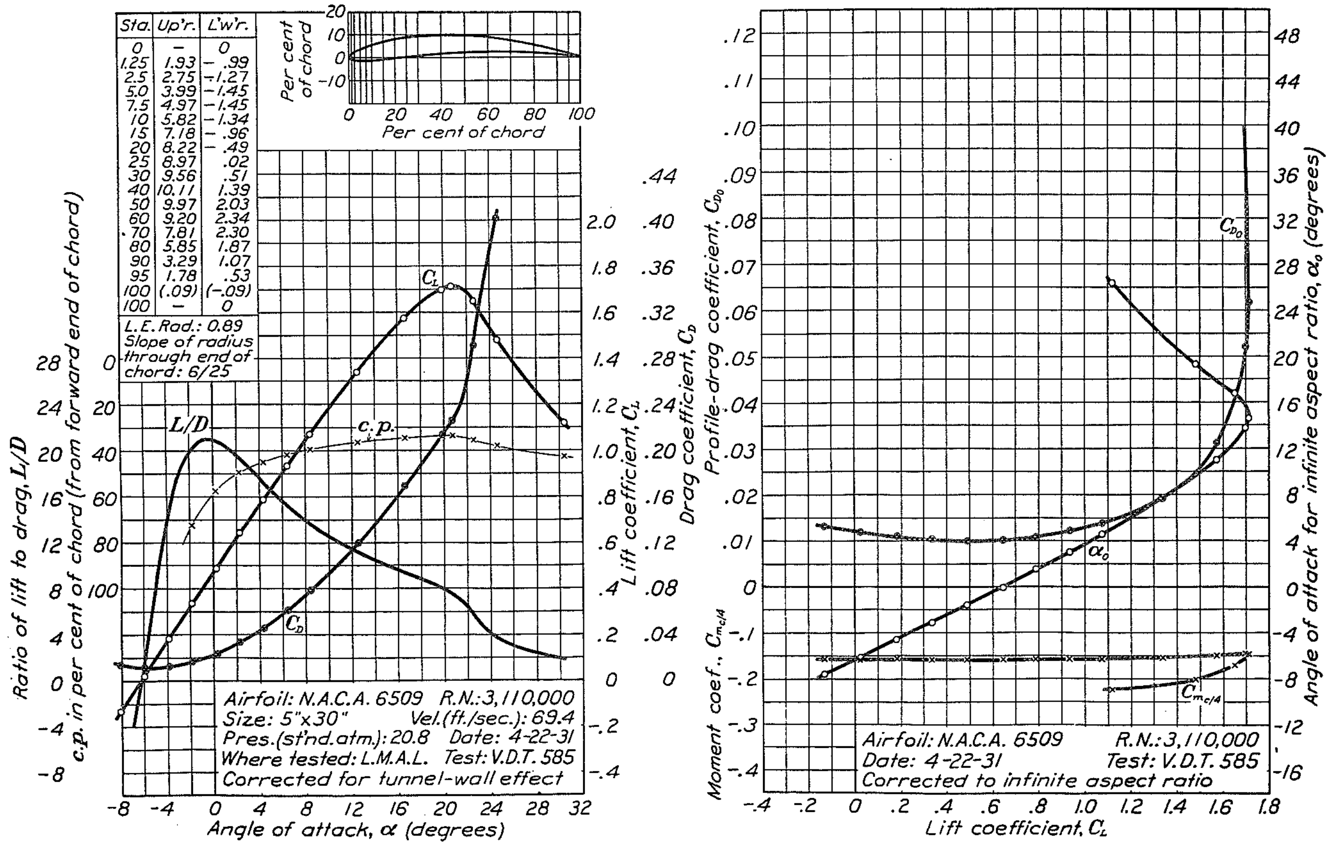
Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.36	−.60
2.5	2.00	−.70
5.0	3.01	−.62
7.5	3.85	−.43
10	4.58	−.19
15	5.78	.37
20	6.74	.95
25	7.49	1.51
30	8.06	2.03
40	8.66	2.84
50	8.65	3.35
60	8.06	3.48
70	6.89	3.21
80	5.17	2.52
90	2.90	1.43
95	1.57	.73
100	(.06)	(−.06)
100	—	0

L.E. Rad.: 0.40
Slope of radius through end of chord: 6/25

Airfoil: N.A.C.A. 6506 R.N.: 3,170,000
Size: 5"x30" Vel.(ft./sec.): 68.5
Pres.(st'nd.atm.): 21.1 Date: 4-23-31
Where tested: L.M.A.L. Test: V.D.T. 586
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6506 R.N.: 3,170,000
Date: 4-23-31 Test: V.D.T. 586
Corrected to infinite aspect ratio

FIGURE 64.—N.A.C.A. 6506 airfoil.



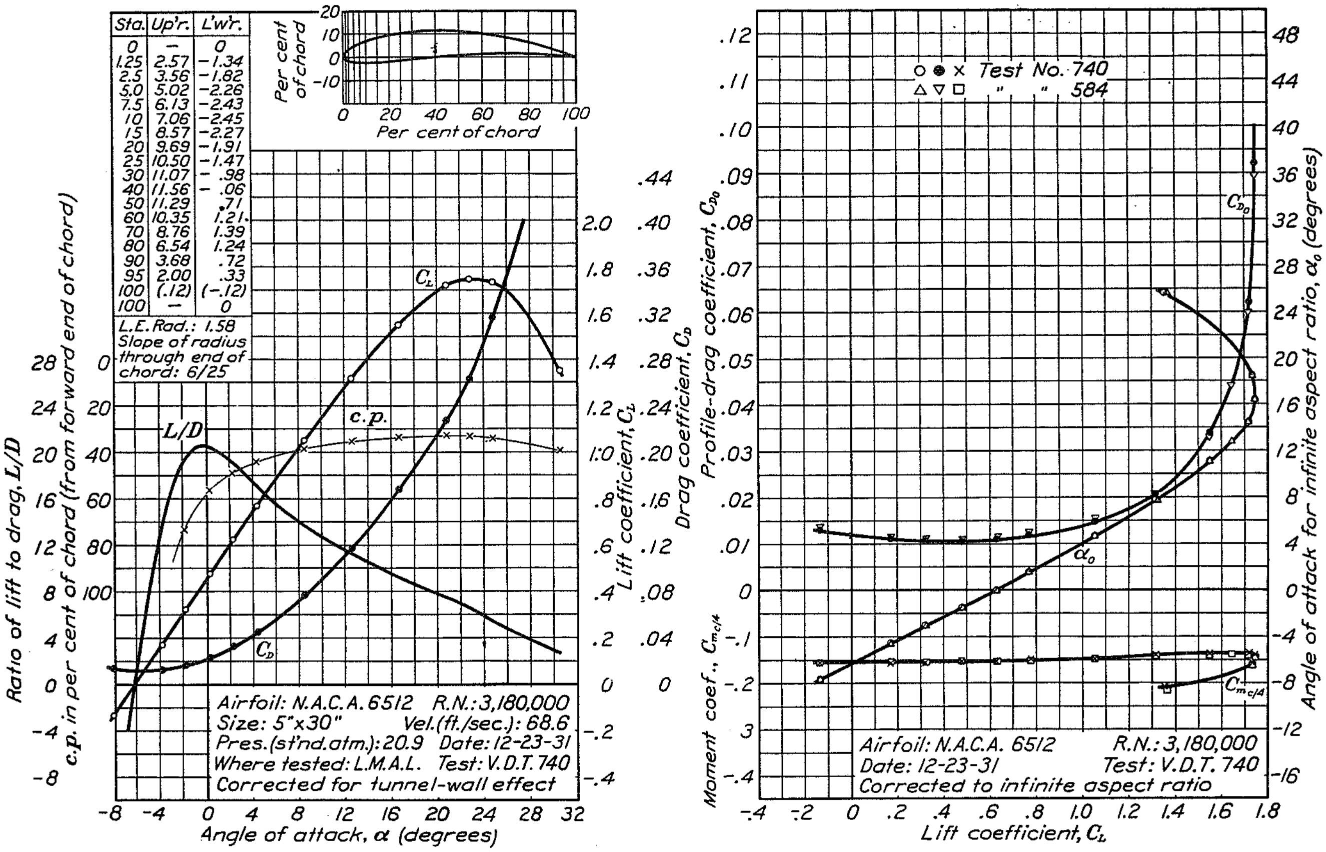
Sta.	Up'r.	L'w'r.
0	—	0
1.25	1.93	−.99
2.5	2.75	−1.27
5.0	3.99	−1.45
7.5	4.97	−1.45
10	5.82	−1.34
15	7.18	−.96
20	8.22	−.49
25	8.97	.02
30	9.56	.51
40	10.11	1.39
50	9.97	2.03
60	9.20	2.34
70	7.81	2.30
80	5.85	1.87
90	3.29	1.07
95	1.78	.53
100	(.09)	(−.09)
100	—	0

L.E. Rad.: 0.89
Slope of radius through end of chord: 6/25

Airfoil: N.A.C.A. 6509 R.N.: 3,110,000
Size: 5"x30" Vel.(ft./sec.): 69.4
Pres.(st'nd.atm.): 20.8 Date: 4-22-31
Where tested: L.M.A.L. Test: V.D.T. 585
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6509 R.N.: 3,110,000
Date: 4-22-31 Test: V.D.T. 585
Corrected to infinite aspect ratio

FIGURE 65.—N.A.C.A. 6509 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.57	−1.34
2.5	3.56	−1.82
5.0	5.02	−2.26
7.5	6.13	−2.43
10	7.06	−2.45
15	8.57	−2.27
20	9.69	−1.91
25	10.50	−1.47
30	11.07	− .98
40	11.56	− .06
50	11.29	.71
60	10.35	1.21
70	8.76	1.39
80	6.54	1.24
90	3.68	.72
95	2.00	.33
100	(.12)	(−.12)
100	—	0

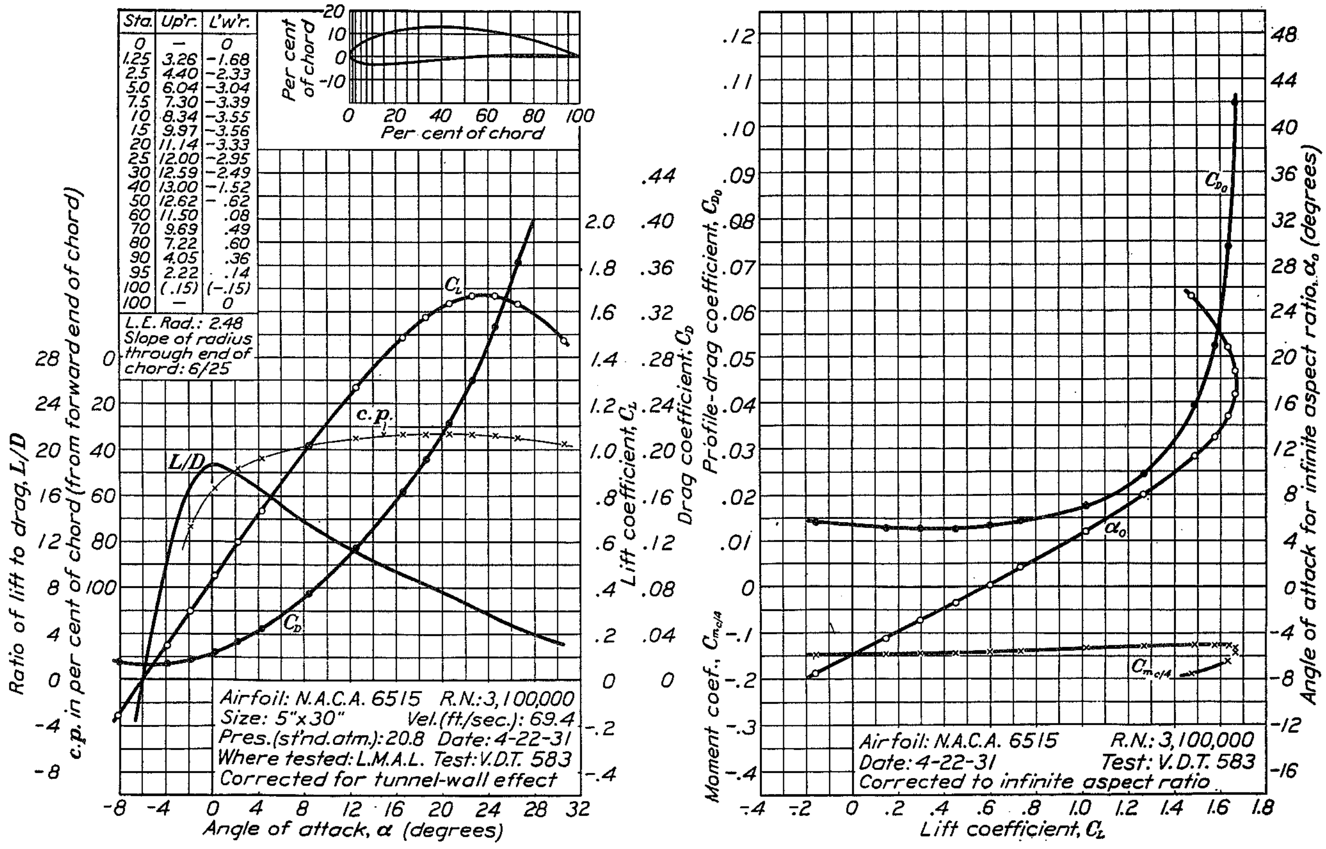
L.E. Rad.: 1.58
Slope of radius through end of chord: 6/25

Airfoil: N.A.C.A. 6512 R.N.: 3,180,000
Size: 5"x30" Vel.(ft./sec.): 68.6
Pres.(st'nd.atm.): 20.9 Date: 12-23-31
Where tested: L.M.A.L. Test: V.D.T. 740
Corrected for tunnel-wall effect

○ ● × Test No. 740
△ ▽ □ " " 584

Airfoil: N.A.C.A. 6512 R.N.: 3,180,000
Date: 12-23-31 Test: V.D.T. 740
Corrected to infinite aspect ratio

FIGURE 66.—N.A.C.A. 6512 airfoil.



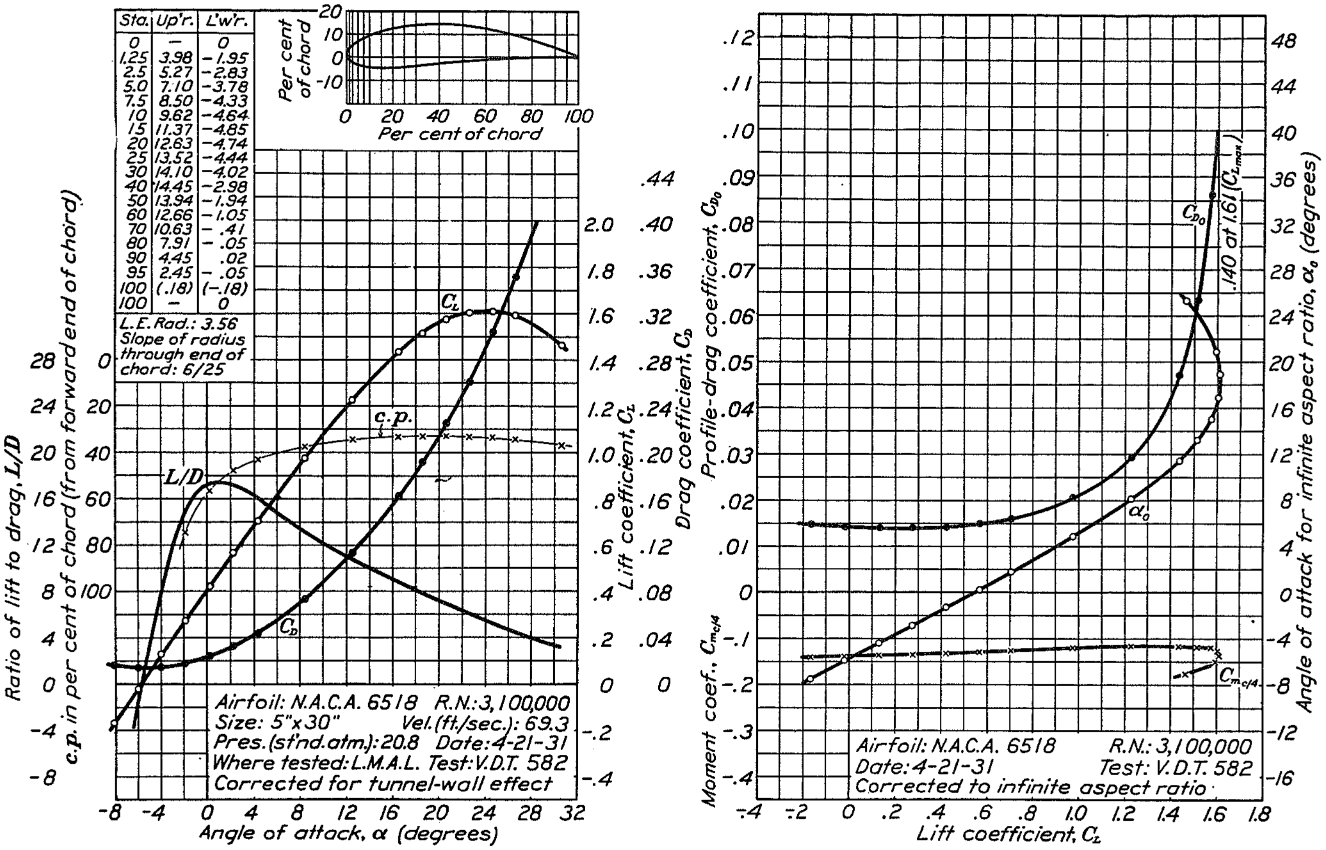
Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.26	−1.68
2.5	4.40	−2.33
5.0	6.04	−3.04
7.5	7.30	−3.39
10	8.34	−3.55
15	9.97	−3.56
20	11.14	−3.33
25	12.00	−2.95
30	12.59	−2.49
40	13.00	−1.52
50	12.62	− .62
60	11.50	.08
70	9.69	.49
80	7.22	.60
90	4.05	.36
95	2.22	.14
100	(.15)	(−.15)
100	—	0

L.E. Rad.: 2.48
Slope of radius through end of chord: 6/25

Airfoil: N.A.C.A. 6515 R.N.: 3,100,000
Size: 5"x30" Vel.(ft./sec.): 69.4
Pres.(st'nd.atm.): 20.8 Date: 4-22-31
Where tested: L.M.A.L. Test: V.D.T. 583
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6515 R.N.: 3,100,000
Date: 4-22-31 Test: V.D.T. 583
Corrected to infinite aspect ratio

FIGURE 67.—N.A.C.A. 6515 airfoil.



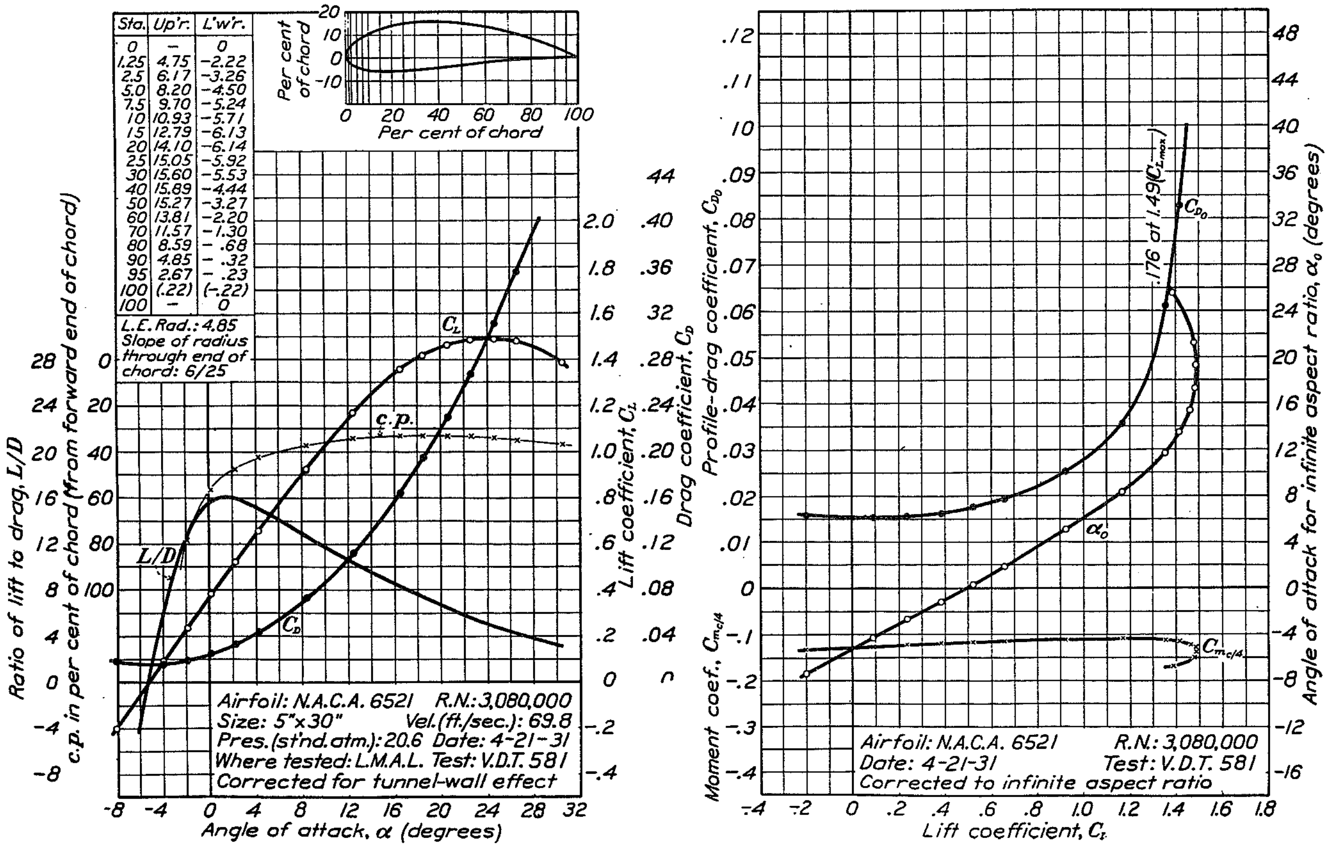
Sta.	Up'r.	L'w'r.
0	—	0
1.25	3.98	−1.95
2.5	5.27	−2.83
5.0	7.10	−3.78
7.5	8.50	−4.33
10	9.62	−4.64
15	11.37	−4.85
20	12.63	−4.74
25	13.52	−4.44
30	14.10	−4.02
40	14.45	−2.98
50	13.94	−1.94
60	12.66	−1.05
70	10.63	− .41
80	7.91	− .05
90	4.45	.02
95	2.45	− .05
100	(.18)	(−.18)
100	—	0

L.E. Rad.: 3.56
Slope of radius through end of chord: 6/25

Airfoil: N.A.C.A. 6518 R.N.: 3,100,000
Size: 5"x30" Vel. (ft./sec.): 69.3
Pres. (st'nd. atm.): 20.8 Date: 4-21-31
Where tested: L.M.A.L. Test: V.D.T. 582
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6518 R.N.: 3,100,000
Date: 4-21-31 Test: V.D.T. 582
Corrected to infinite aspect ratio

FIGURE 68.—N.A.C.A. 6518 airfoil.



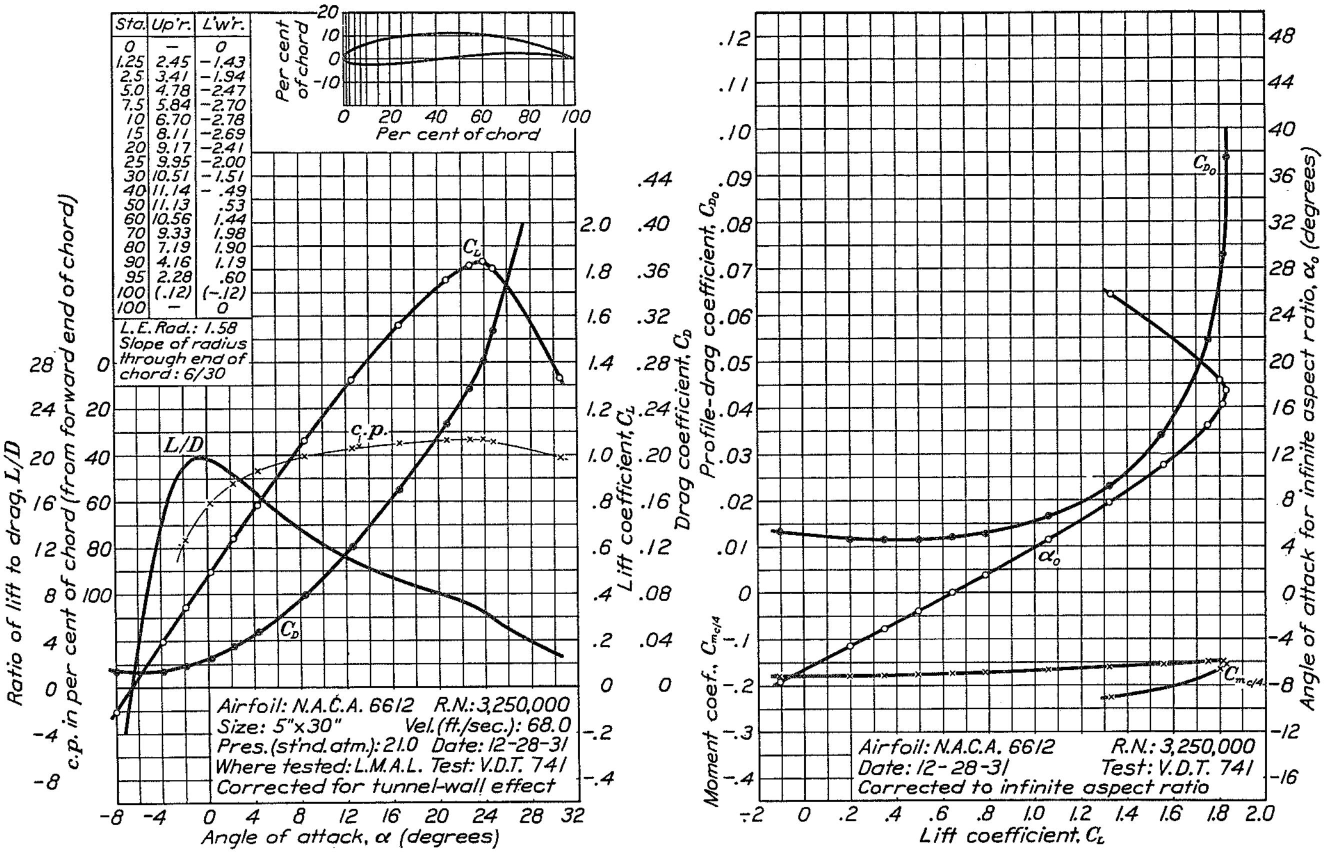
Sta.	Up'r.	L'w'r.
0	—	0
1.25	4.75	−2.22
2.5	6.17	−3.26
5.0	8.20	−4.50
7.5	9.70	−5.24
10	10.93	−5.71
15	12.79	−6.13
20	14.10	−6.14
25	15.05	−5.92
30	15.60	−5.53
40	15.89	−4.44
50	15.27	−3.27
60	13.81	−2.20
70	11.57	−1.30
80	8.59	− .68
90	4.85	− .32
95	2.67	− .23
100	(.22)	(−.22)
100	—	0

L.E. Rad.: 4.85
Slope of radius through end of chord: 6/25

Airfoil: N.A.C.A. 6521 R.N.: 3,080,000
Size: 5"x30" Vel. (ft./sec.): 69.8
Pres. (st'nd. atm.): 20.6 Date: 4-21-31
Where tested: L.M.A.L. Test: V.D.T. 581
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 6521 R.N.: 3,080,000
Date: 4-21-31 Test: V.D.T. 581
Corrected to infinite aspect ratio

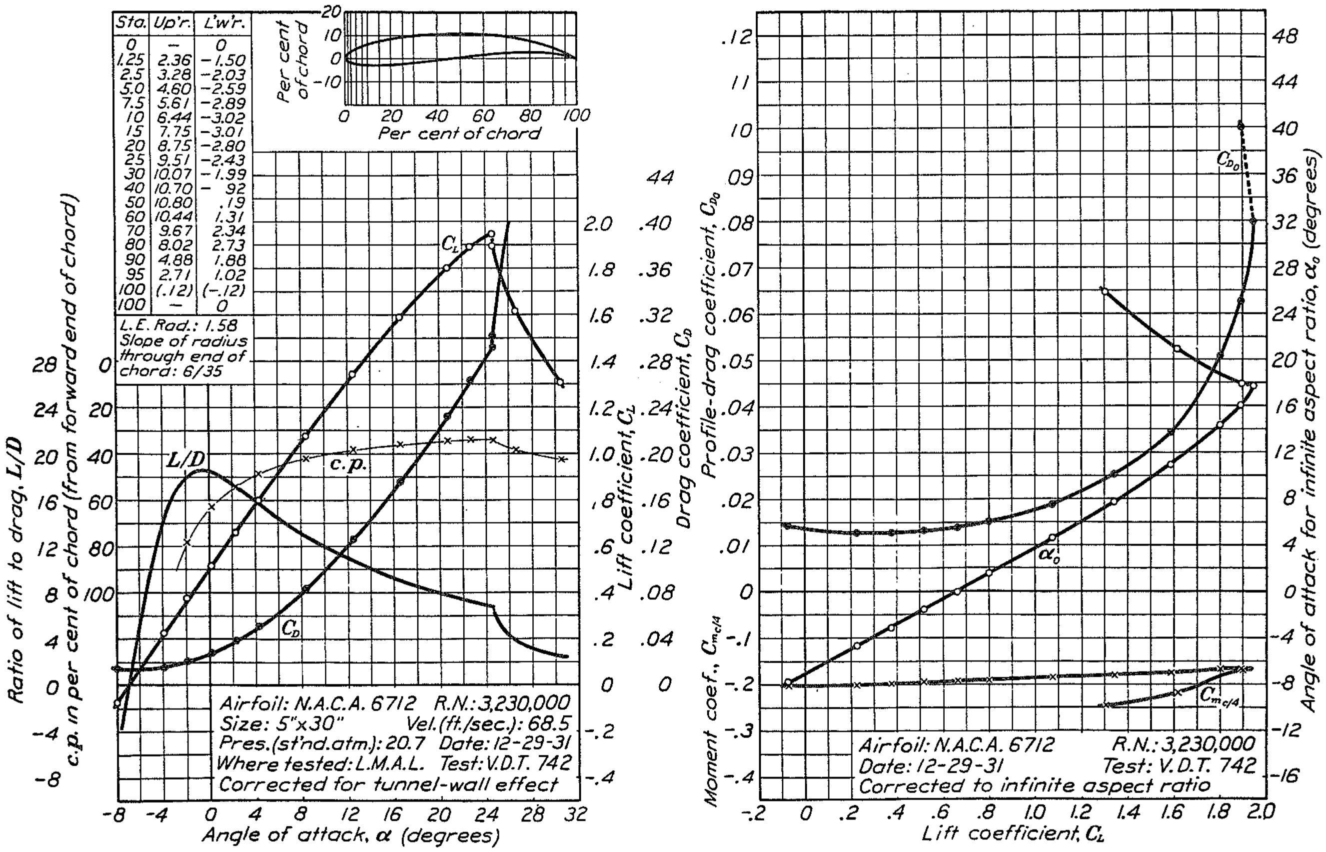
FIGURE 69.—N.A.C.A. 6521 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.45	−1.43
2.5	3.41	−1.94
5.0	4.78	−2.47
7.5	5.84	−2.70
10	6.70	−2.78
15	8.11	−2.69
20	9.17	−2.41
25	9.95	−2.00
30	10.51	−1.51
40	11.14	− .49
50	11.13	.53
60	10.56	1.44
70	9.33	1.98
80	7.19	1.90
90	4.16	1.19
95	2.28	.60
100	(.12)	(−.12)
100	—	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 6/30

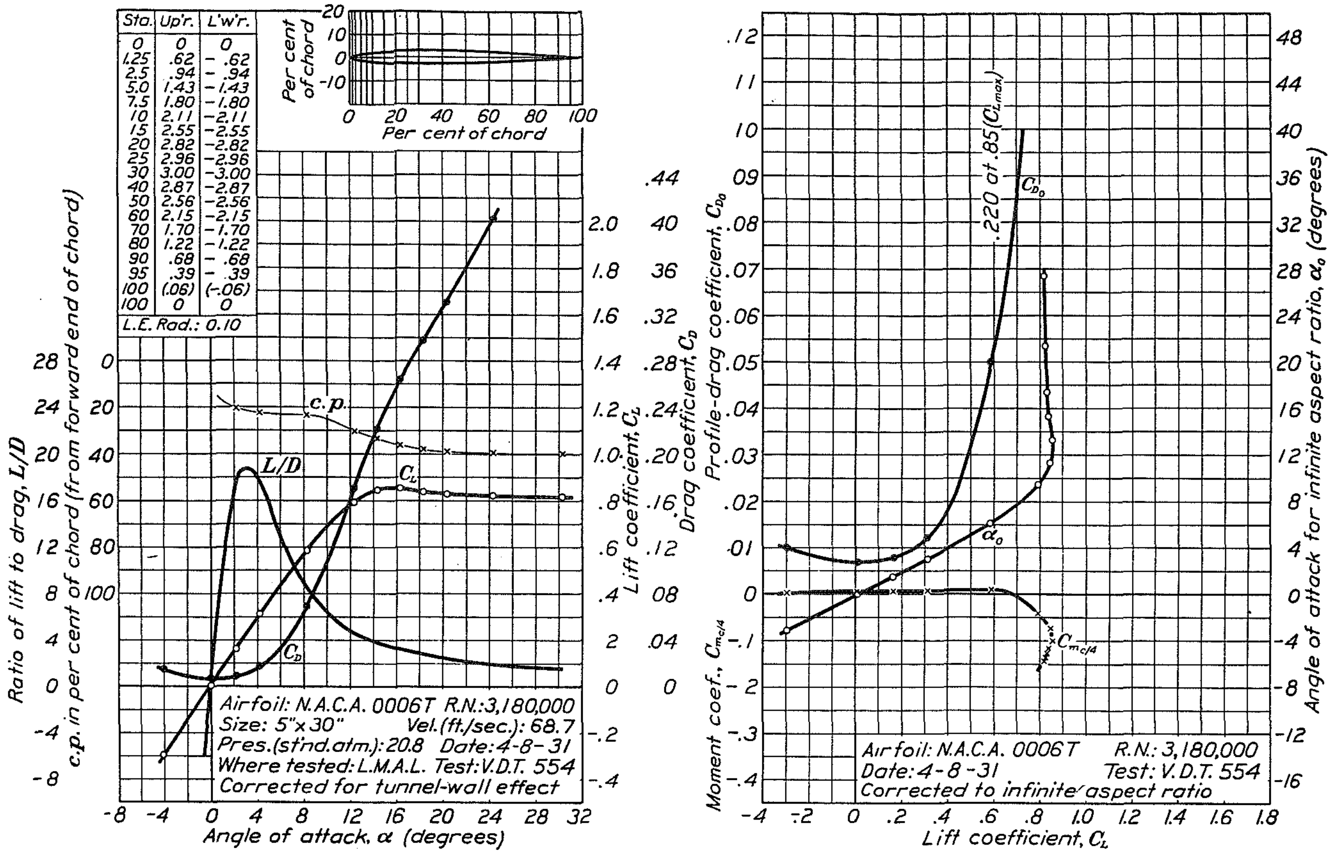
FIGURE 70.—N.A.C.A. 6612 airfoil.



Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.36	−1.50
2.5	3.28	−2.03
5.0	4.60	−2.59
7.5	5.61	−2.89
10	6.44	−3.02
15	7.75	−3.01
20	8.75	−2.80
25	9.51	−2.43
30	10.07	−1.99
40	10.70	− 92
50	10.80	.19
60	10.44	1.31
70	9.67	2.34
80	8.02	2.73
90	4.88	1.88
95	2.71	1.02
100	(.12)	(−.12)
100	—	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 6/35

FIGURE 71.—N.A.C.A. 6712 airfoil.



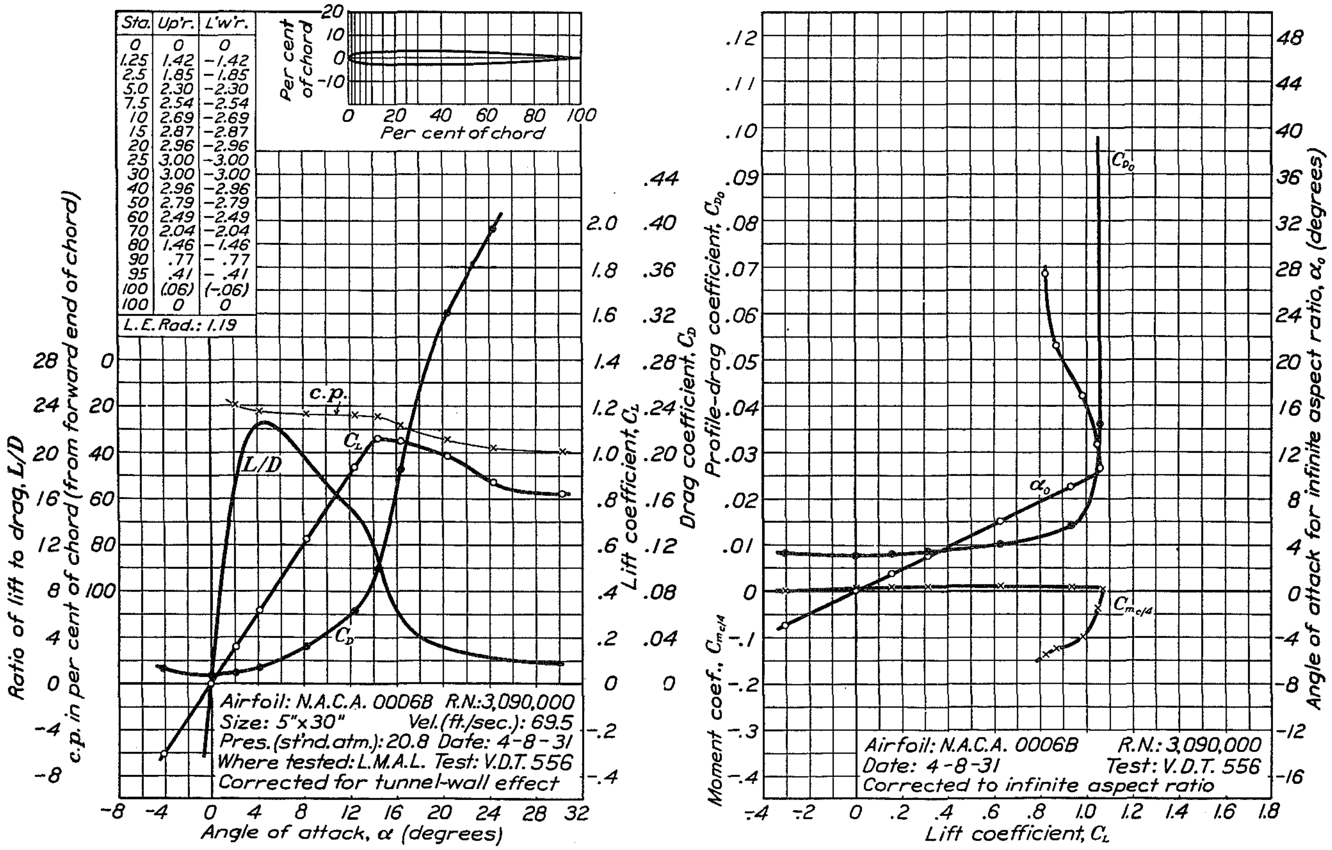
Sta.	Up'r.	L'w'r.
0	0	0
1.25	.62	− .62
2.5	.94	− .94
5.0	1.43	−1.43
7.5	1.80	−1.80
10	2.11	−2.11
15	2.55	−2.55
20	2.82	−2.82
25	2.96	−2.96
30	3.00	−3.00
40	2.87	−2.87
50	2.56	−2.56
60	2.15	−2.15
70	1.70	−1.70
80	1.22	−1.22
90	.68	− .68
95	.39	− .39
100	(.06)	(−.06)
100	0	0

L.E. Rad.: 0.10

Airfoil: N.A.C.A. 0006T R.N.: 3,180,000
Size: 5"×30" Vel.(ft./sec.): 68.7
Pres.(stnd.atm.): 20.8 Date: 4-8-31
Where tested: L.M.A.L. Test: V.D.T. 554
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 0006T R.N.: 3,180,000
Date: 4-8-31 Test: V.D.T. 554
Corrected to infinite aspect ratio

FIGURE 72.—N.A.C.A. 0006T airfoil.



Sta.	Up'r.	L'w'r.
0	0	0
1.25	1.42	−1.42
2.5	1.85	−1.85
5.0	2.30	−2.30
7.5	2.54	−2.54
10	2.69	−2.69
15	2.87	−2.87
20	2.96	−2.96
25	3.00	−3.00
30	3.00	−3.00
40	2.96	−2.96
50	2.79	−2.79
60	2.49	−2.49
70	2.04	−2.04
80	1.46	−1.46
90	.77	− .77
95	.41	− .41
100	(.06)	(−.06)
100	0	0

L.E. Rad.: 1.19

Airfoil: N.A.C.A. 0006B R.N.: 3,090,000
Size: 5"×30" Vel.(ft./sec.): 69.5
Pres.(stnd.atm.): 20.8 Date: 4-8-31
Where tested: L.M.A.L. Test: V.D.T. 556
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. 0006B R.N.: 3,090,000
Date: 4-8-31 Test: V.D.T. 556
Corrected to infinite aspect ratio

FIGURE 73.—N.A.C.A. 0006B airfoil.

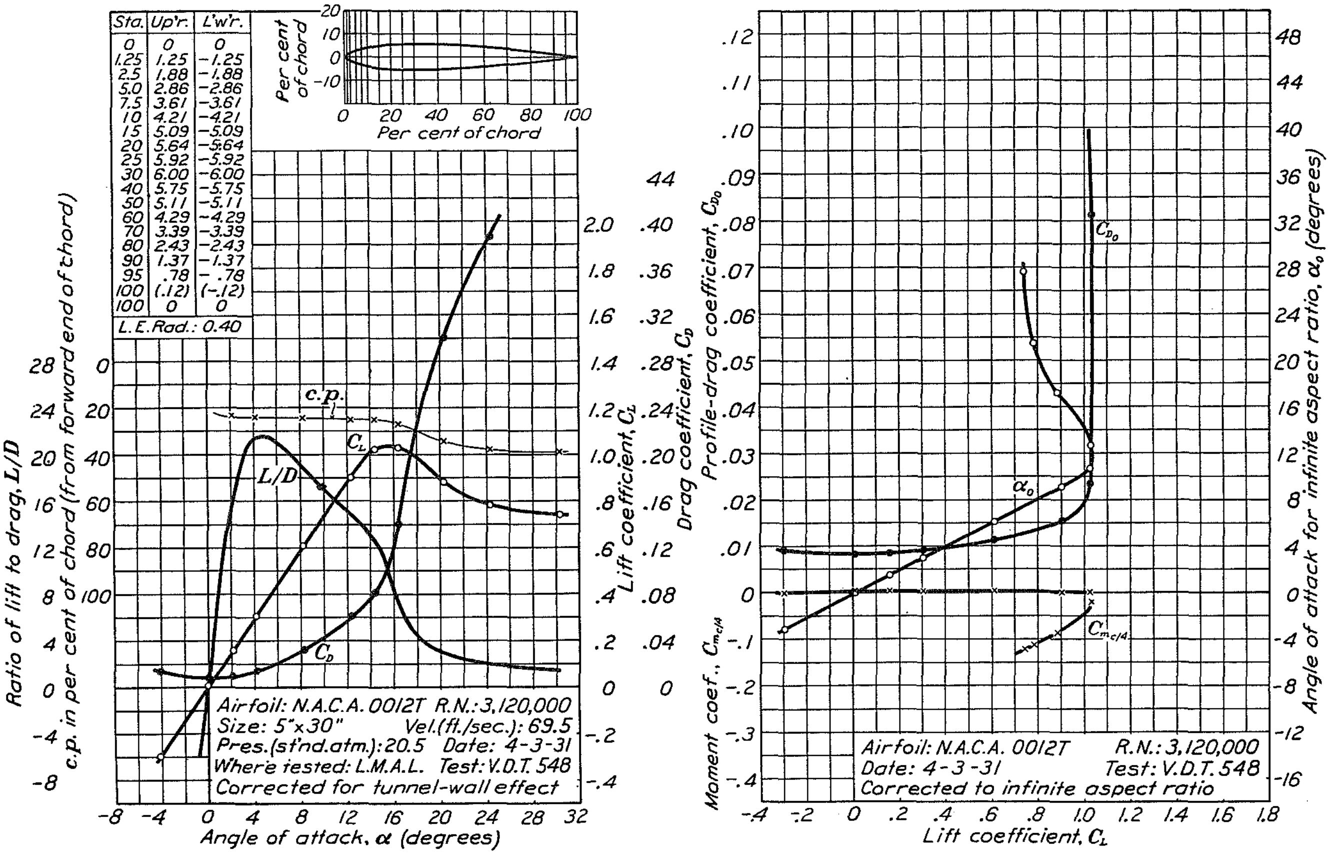


FIGURE 74.—N.A.C.A. 0012T airfoil.

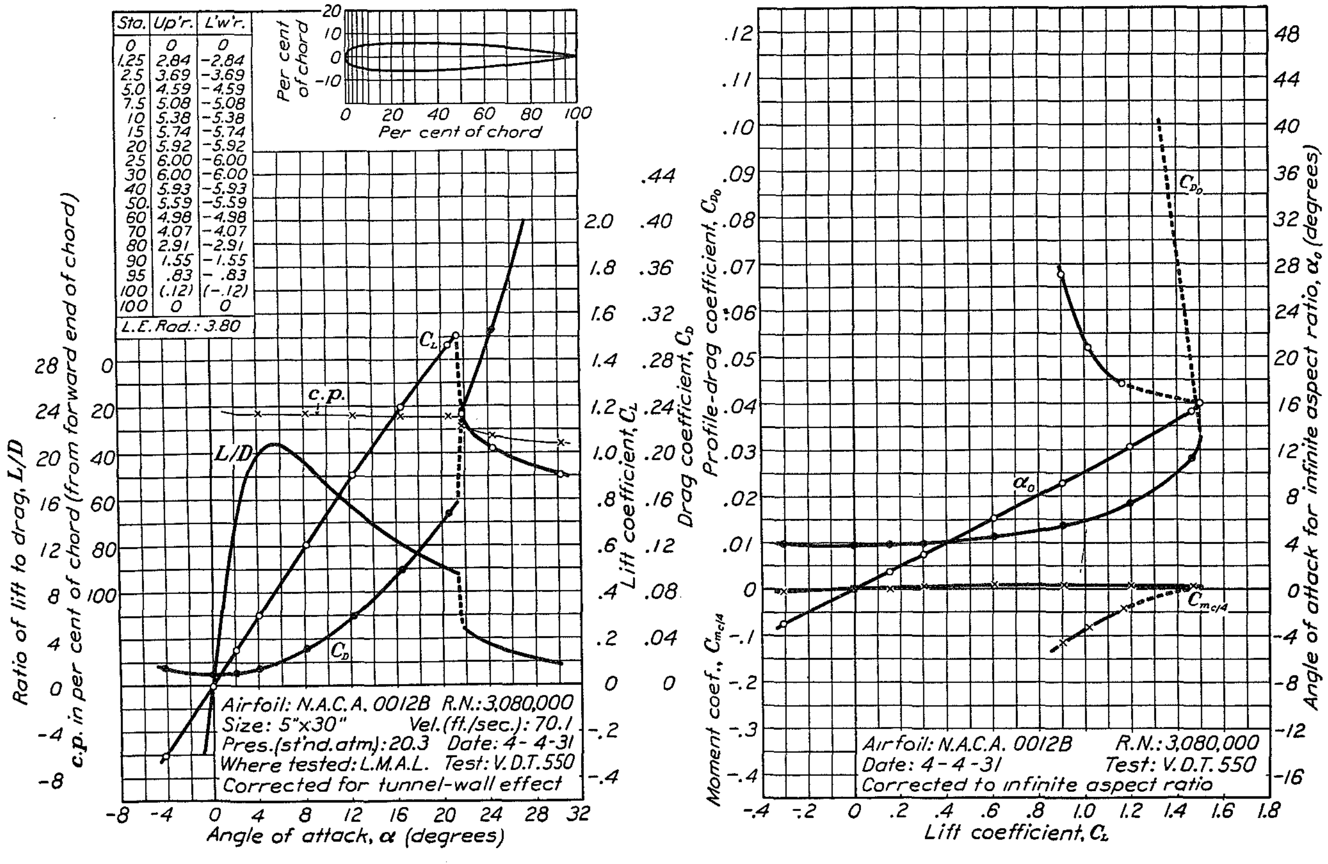
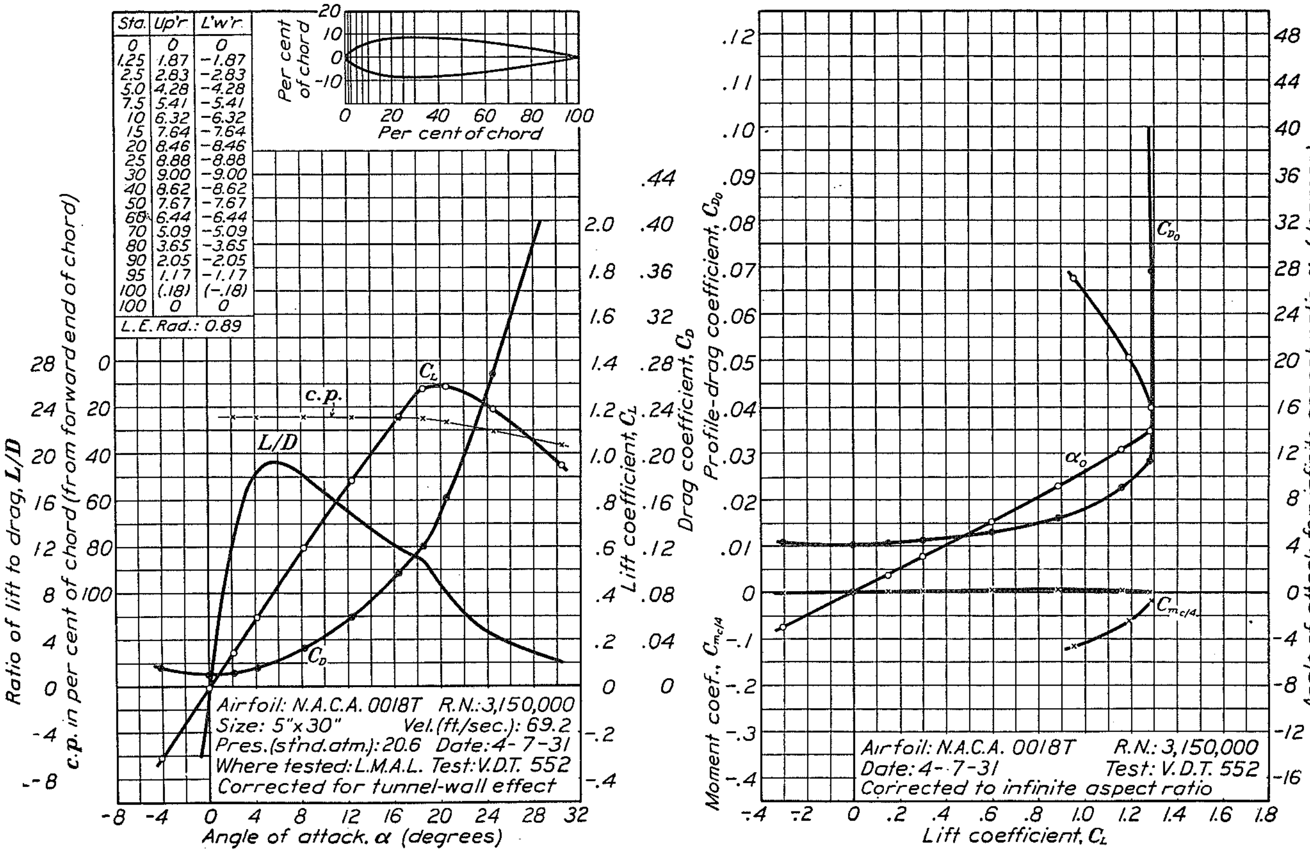
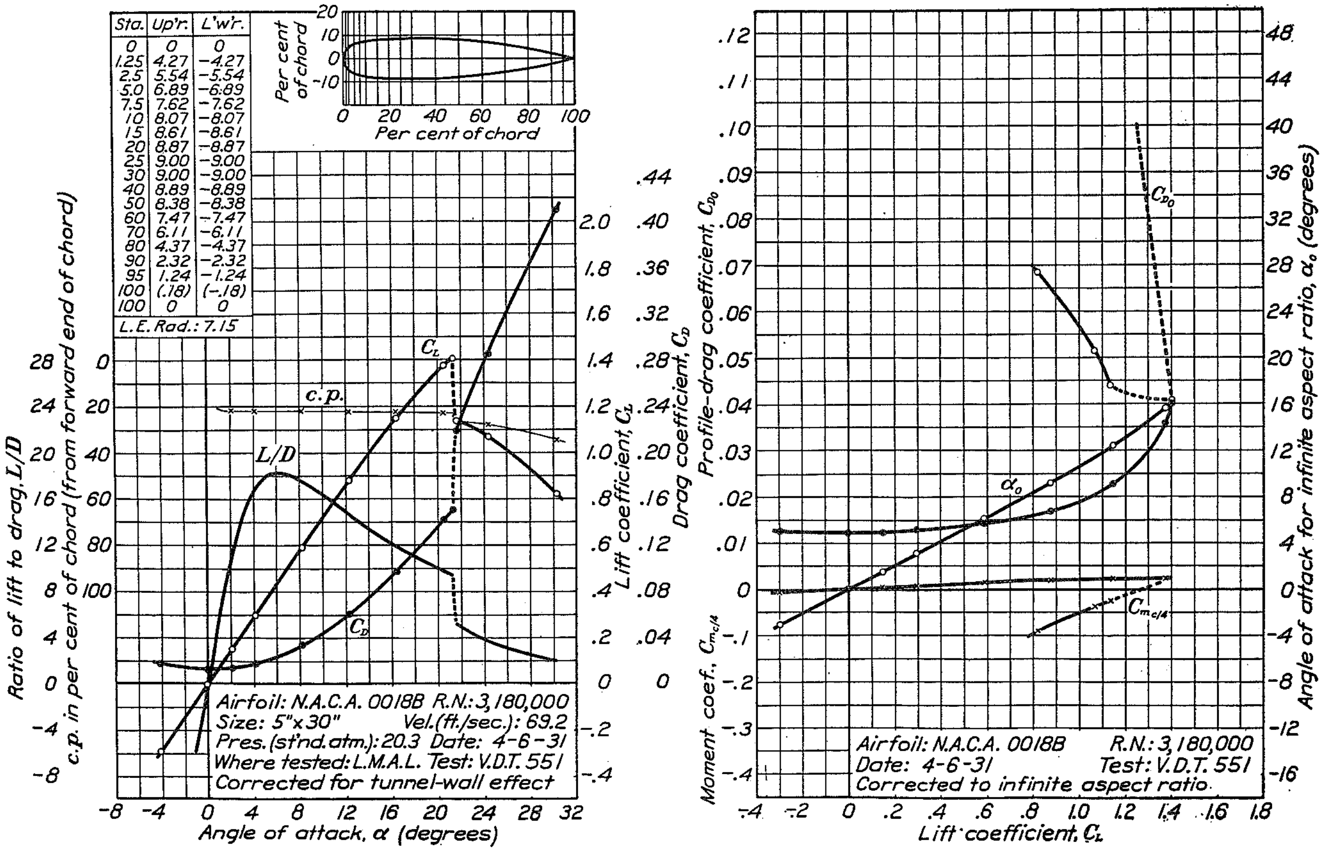


FIGURE 75.—N.A.C.A. 0012B airfoil.



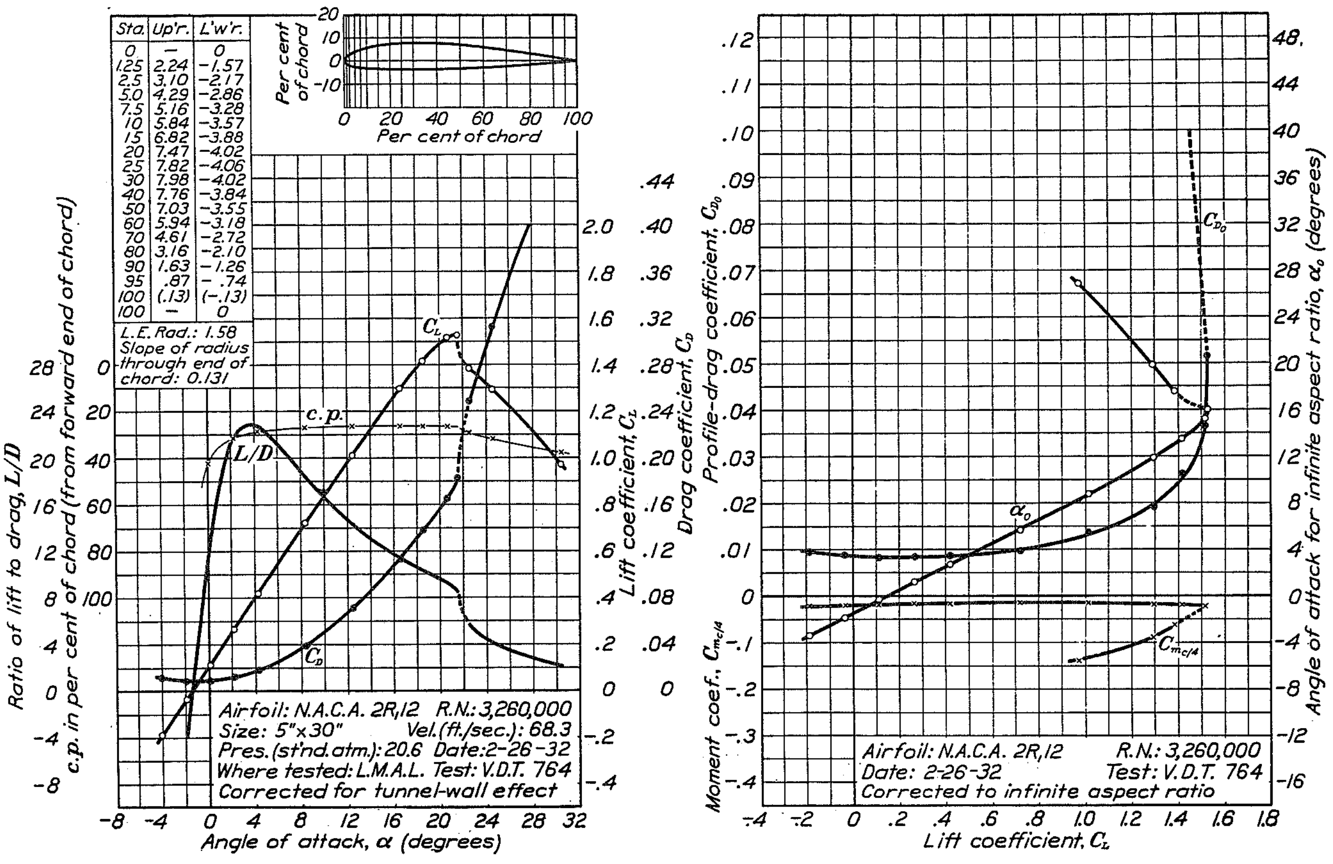
Sta.	Up'r	L'w'r
0	0	0
1.25	1.87	-1.87
2.5	2.83	-2.83
5.0	4.28	-4.28
7.5	5.41	-5.41
10	6.32	-6.32
15	7.64	-7.64
20	8.46	-8.46
25	8.88	-8.88
30	9.00	-9.00
40	8.62	-8.62
50	7.67	-7.67
60	6.44	-6.44
70	5.09	-5.09
80	3.65	-3.65
90	2.05	-2.05
95	1.17	-1.17
100	(.18)	(-.18)
100	0	0
L.E. Rad.: 0.89		

FIGURE 76.—N.A.C.A. 0018T airfoil.



Sta.	Up'r	L'w'r
0	0	0
1.25	4.27	-4.27
2.5	5.54	-5.54
5.0	6.89	-6.89
7.5	7.62	-7.62
10	8.07	-8.07
15	8.61	-8.61
20	8.87	-8.87
25	9.00	-9.00
30	9.00	-9.00
40	8.89	-8.89
50	8.38	-8.38
60	7.47	-7.47
70	6.11	-6.11
80	4.37	-4.37
90	2.32	-2.32
95	1.24	-1.24
100	(.18)	(-.18)
100	0	0
L.E. Rad.: 7.15		

FIGURE 77.—N.A.C.A. 0018B airfoil.



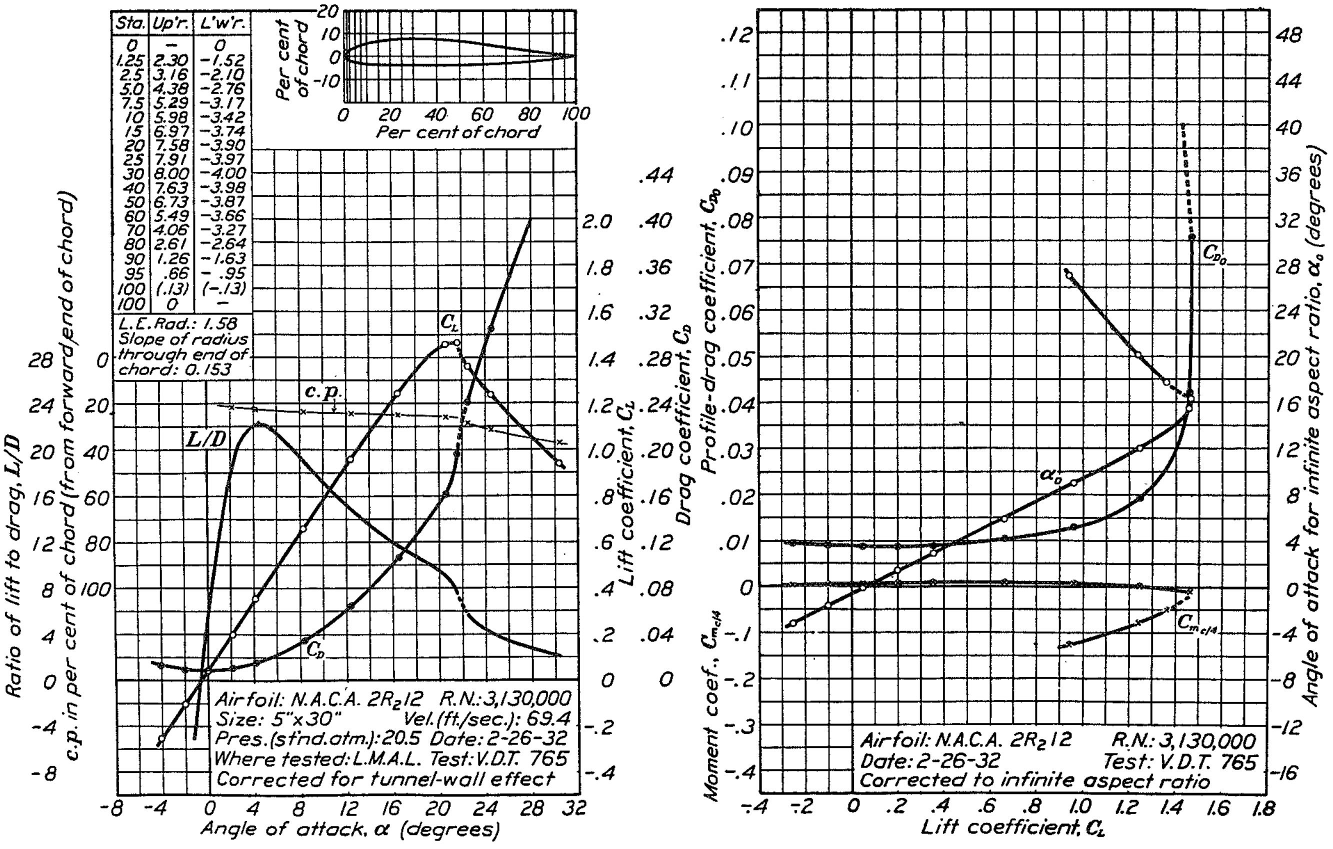
Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.24	−1.57
2.5	3.10	−2.17
5.0	4.29	−2.86
7.5	5.16	−3.28
10	5.84	−3.57
15	6.82	−3.88
20	7.47	−4.02
25	7.82	−4.06
30	7.98	−4.02
40	7.76	−3.84
50	7.03	−3.55
60	5.94	−3.18
70	4.61	−2.72
80	3.16	−2.10
90	1.63	−1.26
95	.87	− .74
100	(.13)	(−.13)
100	—	0

L.E. Rad.: 1.58
Slope of radius through end of chord: 0.131

Airfoil: N.A.C.A. $2R_112$ R.N.: 3,260,000
Size: 5"x30" Vel. (ft./sec.): 68.3
Pres. (st'nd. atm.): 20.6 Date: 2-26-32
Where tested: L.M.A.L. Test: V.D.T. 764
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. $2R_112$ R.N.: 3,260,000
Date: 2-26-32 Test: V.D.T. 764
Corrected to infinite aspect ratio

FIGURE 78.—N.A.C.A. $2R_112$ airfoil.



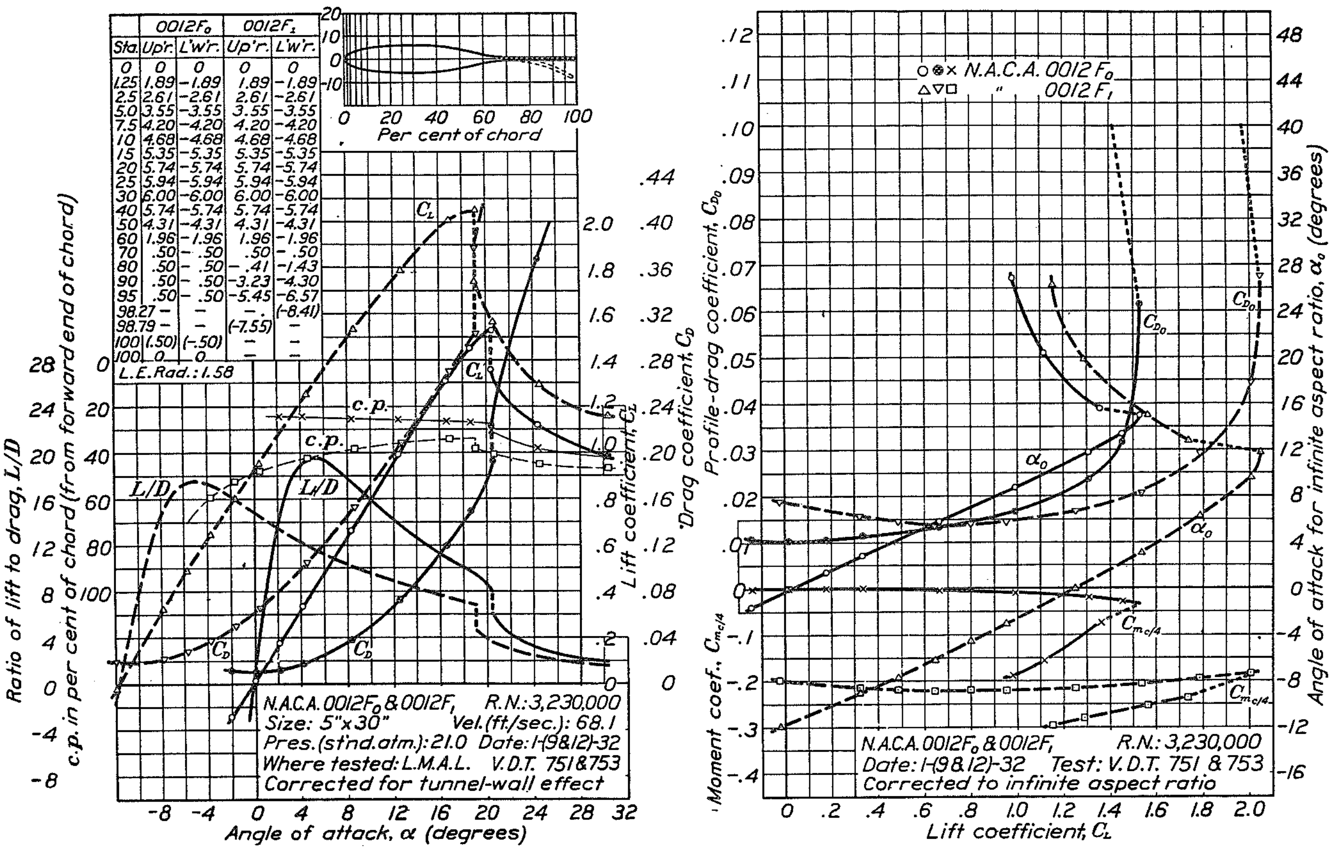
Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.30	−1.52
2.5	3.16	−2.10
5.0	4.38	−2.76
7.5	5.29	−3.17
10	5.98	−3.42
15	6.97	−3.74
20	7.58	−3.90
25	7.91	−3.97
30	8.00	−4.00
40	7.63	−3.98
50	6.73	−3.87
60	5.49	−3.66
70	4.06	−3.27
80	2.61	−2.64
90	1.26	−1.63
95	.66	− .95
100	(.13)	(−.13)
100	0	—

L.E. Rad.: 1.58
Slope of radius through end of chord: 0.153

Airfoil: N.A.C.A. $2R_212$ R.N.: 3,130,000
Size: 5"x30" Vel. (ft./sec.): 69.4
Pres. (st'nd. atm.): 20.5 Date: 2-26-32
Where tested: L.M.A.L. Test: V.D.T. 765
Corrected for tunnel-wall effect

Airfoil: N.A.C.A. $2R_212$ R.N.: 3,130,000
Date: 2-26-32 Test: V.D.T. 765
Corrected to infinite aspect ratio

FIGURE 79.—N.A.C.A. $2R_212$ airfoil.



	0012F₀		0012F₁	
Sta.	Up'r.	L'w'r.	Up'r.	L'w'r.
0	0	0	0	0
1.25	1.89	−1.89	1.89	−1.89
2.5	2.61	−2.61	2.61	−2.61
5.0	3.55	−3.55	3.55	−3.55
7.5	4.20	−4.20	4.20	−4.20
10	4.68	−4.68	4.68	−4.68
15	5.35	−5.35	5.35	−5.35
20	5.74	−5.74	5.74	−5.74
25	5.94	−5.94	5.94	−5.94
30	6.00	−6.00	6.00	−6.00
40	5.74	−5.74	5.74	−5.74
50	4.31	−4.31	4.31	−4.31
60	1.96	−1.96	1.96	−1.96
70	.50	− .50	.50	− .50
80	.50	− .50	− .41	−1.43
90	.50	− .50	−3.23	−4.30
95	.50	− .50	−5.45	−6.57
98.27	−	−	−	(−8.41)
98.79	−	−	(−7.55)	−
100	(.50)	(−.50)	−	−
100	0	0	−	−

L.E. Rad.: 1.58

FIGURE 80.—N.A.C.A. 0012F₀ and 0012F₁ airfoils.

PRECISION

A general discussion of the errors and corrections involved in airfoil testing in the variable-density tunnel is included in reference 8. In connection with this report, it was hoped that a more specific discussion of the various sources of error and separate estimates of the various errors might be given. However, after a careful study of all the measurements it became apparent that practically all the errors may be regarded as accidental; that is, of the type the magnitude of which may best be estimated from the dispersion of the results of independent repeat measurements. The major portion of these errors is caused by insufficient sensitivity of the balance and manometers, by the personal error involved in reading mean values of slightly fluctuating quantities, and by the error due to slight surface imperfections in the model. The last is perhaps the most serious source of error. The models were carefully finished before each test, but the presence of particles of hard foreign matter in the air stream tended to cause a slight pitting of the leading edge of the model during each test. This pitting was probably the major source of error in connection with the earlier tests, but it was reduced for the later tests when the necessity of a more careful inspection of each model was appreciated. After a considerable period of running the particles in the tunnel were found to become lodged, permitting this source of error to be largely eliminated during the later tests. For this report, however, the effect of the error from this source has been minimized by repeating the tests of many of the airfoils, including all of the symmetrical series originally reported in reference 2.

The magnitude of all such accidental errors was judged from the results of repeat tests of many airfoils, and from the results of approximately 25 tests of one airfoil that were made periodically throughout the investigation to check the consistency of the measurements. The accidental errors in the results presented in this report are believed to be within the limits indicated in the following table:

α	$\pm 0.15°$
$C_{L_{max}}$	$\begin{cases} 0.01 \\ -0.03 \end{cases}$
$C_{m_{c/4}}$	± 0.003
$C_{D_0}(C_L=0)$	$\begin{cases} 0.0006 \\ -0.0002 \end{cases}$
$C_{D_0}(C_L=1)$	$\begin{cases} 0.0015 \\ -0.0008 \end{cases}$

In addition to the consideration of the accidental errors, all measurements were carefully analyzed to consider possible sources of errors of the type that would not be apparent from the dispersion of the results of repeat tests. A rather large (approximately 1.5 percent) error of this type is present in all the air-velocity measurements resulting from a reduction in the apparent weight of the manometer liquid when the density of the air in the tunnel is raised to that corresponding to a pressure of 20 atmospheres. The effects of this error, however, are reduced by the presence of another error in the air-velocity measurements due to the blocking effects of the model in the tunnel. The measured coefficients, obtained by dividing the measured forces by $\frac{1}{2}\rho V^2$, as well as the derived coefficients are, of course, affected by errors in the air-velocity measurement. Aside from this source of error, it is believed that only two other sources need be considered: first, the deflection of the model and supports under the air load; and second, the interference of the airfoil supports on the airfoil. The angle of attack and the moment coefficient are affected by the deflection of the airfoil and supports. The error in angle of attack, which is proportional to $C_{m_{c/4}}$, was found to be approximately $-0.1°$ for an airfoil having a moment coefficient of -0.075. The error from this source in the moment coefficient is inappreciable at zero lift, but at a lift coefficient of 1 may amount to -0.001. The errors resulting from the support interference are more difficult to evaluate, but tests of airfoils with different support arrangements lead to the belief that they are within the limits indicated in the following table:

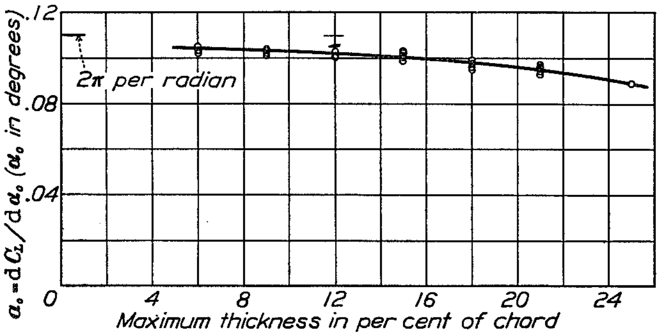


FIGURE 81.—Variation of lift-curve slope with thickness.

α	$\pm 0.05°$
$C_{L_{max}}$	0.00 -0.02
$C_{m_{c/4}}$	± 0.001
$C_{D_0}(C_L=0)$	0.0002 0.0000
$C_{D_0}(C_L=1)$	± 0.0010

The tunnel-wall and induced-drag corrections applied to obtain the airfoil section characteristics might also be treated as sources of systematic errors. Such errors need not be considered, however, if the section characteristics are defined as the measured characteristics with certain calculated corrections applied. Errors in the tunnel-wall corrections, however, should be considered when the results from different wind tunnels are compared. For consideration of these errors, the reader is referred to references 9 and 10.

For the purpose of comparing the results from different wind tunnels and of applying these results to airplanes in flight, it is also necessary to consider the effects of air-stream turbulence. In air streams having different degrees of turbulence, the value of the Reynolds Number cannot be considered as a sufficient measure of the effective dynamic scale of the flow. The airfoil characteristics presented in this report were obtained at a value of the Reynolds Number of approximately 3,000,000, which corresponds roughly to the Reynolds Number attained in flight by a medium-sized airplane flying near its stalling speed. Consideration of the effects of the turbulence present in the variable-density tunnel (see references 11 and 12) leads, however, to the belief that these results are more nearly directly applicable to the characteristics that would be obtained in flight at larger values of the Reynolds Number.

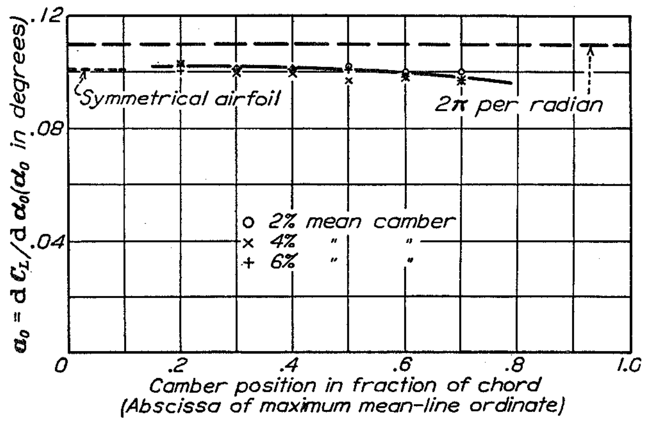


FIGURE 82.—Variation of lift-curve slope with camber. Results for 12 percent thick airfoils.

DISCUSSION

The results of this investigation are here discussed and analyzed to indicate the variation of the aerodynamic characteristics with variations in thickness and in mean-line form. For the analysis of the effect of thickness, test data from consecutive tests of airfoils having different thicknesses and the same mean-line form are used. The analysis of the effect of the mean-line form is made with respect to consecutive tests of airfoils of the same thickness (12 percent of the chord) and related mean-line forms. The results are compared, where possible, with the results predicted by thin-airfoil theory, a summary of which is presented in the appendix.

LIFT

Lift curve.—In the usual working range of an airfoil section the lift coefficient may be expressed as a linear function of the angle of attack

$$C_L = a_0 \ (\alpha_0 - \alpha_{L_0})$$

where a_0 is the slope of the lift curve for the wing of infinite aspect ratio and α_{L_0} is the angle of attack at zero lift.

The variation of the lift-curve slope with thickness is shown in figure 81. The points on the figure represent the deduced slopes as measured in the angular range of low profile drag. These results confirm previous results (reference 1) in that they show the lift-curve slope to decrease with increasing thickness. The camber has very little effect on the slope, as indicated in figure 82, although a rearward movement of the position of the camber tends to decrease the slope slightly. Table II gives the numerical values of the slope in convenient form for noting the general trends with respect to variations in thickness and in camber. It will be noted that all values of the slope lie below the approximate theoretical value for thin wings, 2π per radian; the measured values lie between 95 and 81 percent, approximately, of the theoretical.

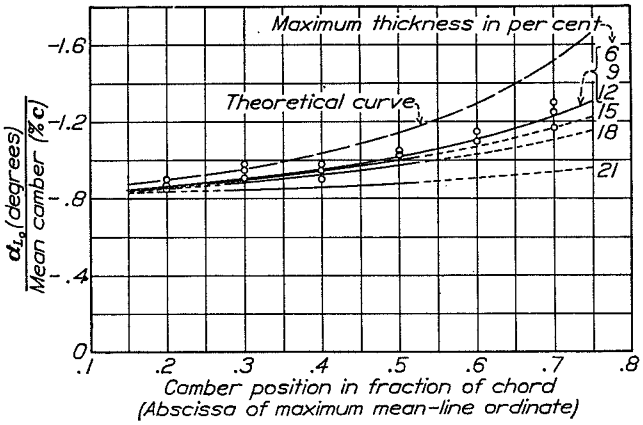


FIGURE 83.—Variation of angle of zero lift with camber. Points shown are for 12 percent thick airfoils. Curves indicate general trends for the different thicknesses.

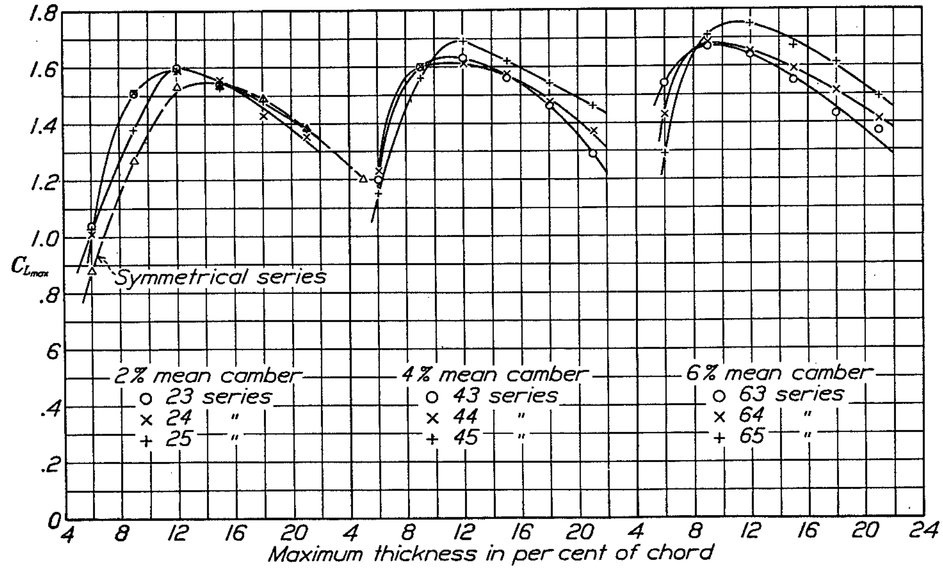


FIGURE 85.—Variation of maximum lift with thickness.

The angle of zero lift is best analyzed by means of a comparison with that predicted by the theory. Thin-airfoil theory states that the angle of zero lift is proportional to the camber if the camber is varied, as with these related airfoils, by scaling the ordinates of a given mean line without altering the camber position. The theory also predicts an increased negative angle as the position of the camber moves back along the chord. The experimental values are compared with the theoretical values in figures 83 and 84. The experimental values lie between 100 and 75 percent, approximately, of the theoretical values, the departure becoming greater with a rearward movement of the position of the camber and with increased thickness (above 9 to 12 percent of the chord). Numerical values of the angle of zero lift are given in table III.

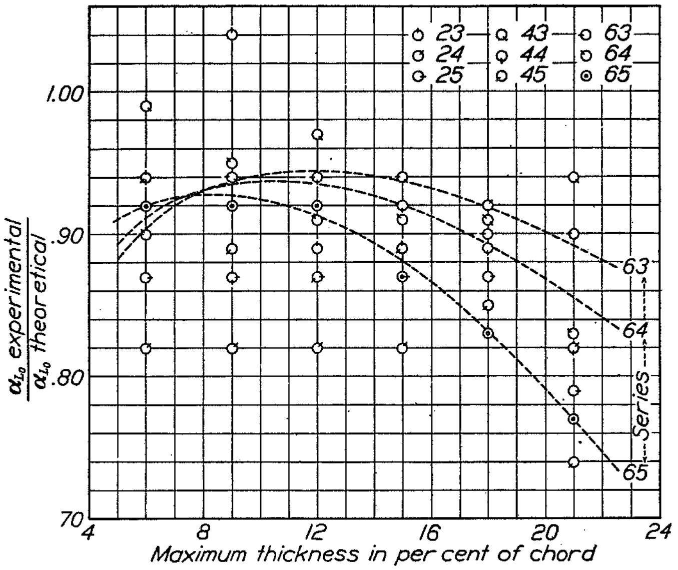


FIGURE 84.—Variation of angle of zero lift with thickness. Numbers refer to mean-camber designation.

Maximum lift.—The variation of the maximum lift coefficient with thickness is shown in figure 85. It will be noted that the highest values are obtained with moderately thick sections (9 to 12 percent of the chord thick, except for the symmetrical sections for which the highest values are obtained with somewhat thicker sections). The variation with camber, shown in figure 86, confirms the expected increase in maximum lift with camber. The gain is small, however, for the normal positions of the camber, but becomes larger as the camber moves either rearward or forward. It will be seen by reference to figure 85 that the camber becomes less effective as the thickness is increased. This reduced effectiveness of the camber is in agreement with a conclusion reached in reference 13 that for airfoils having a thickness ratio of approximately 20 percent of the chord, camber is of questionable value. Numerical values of the maximum lift coefficient are given in table IV.

Air-flow discontinuities.—These and other wind-tunnel tests indicate that at the attitude of maximum lift the air forces on certain airfoils exhibit sudden changes which in many instances result in a serious loss of lift. The probable cause of these air-flow discontinuities is discussed briefly in reference 13. The stability or instability of the air flow at maximum lift may be judged by the character of the lift-curve peaks indicated for the various airfoils. The curves are classified into three general types as noted in table IV, but the degree of stability is difficult to judge. It may be generally concluded that improved stability may be obtained by (1) having a small leading-edge radius, which causes an early breakdown of the flow with a consequent low value of the maximum lift, (2) increasing the thickness (beyond the normal thickness ratios), or (3) increasing the camber (for airfoils having normal camber positions; i.e., 0.3c to 0.5c).

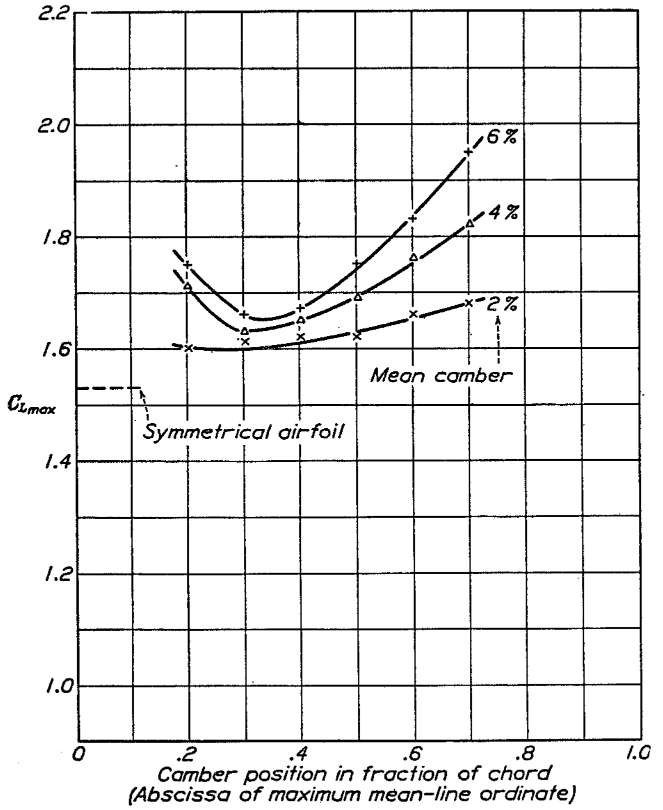


FIGURE 86.—Variation of maximum lift with camber. Results for 12 percent thick airfoils.

MOMENT

Thin-airfoil theory separates the air forces acting on any airfoil into two parts: First, the forces that produce a couple but no lift (they are dependent only on the shape of the mean line); second, the forces that produce the lift only, the resultant of which acts at a fixed point. We then have in the working range an expression for the total moment taken about any point

$$C_m = C_{m_0} + nC_L$$

where C_{m_0} is the moment coefficient at zero lift and nC_L is the additional moment due to lift.

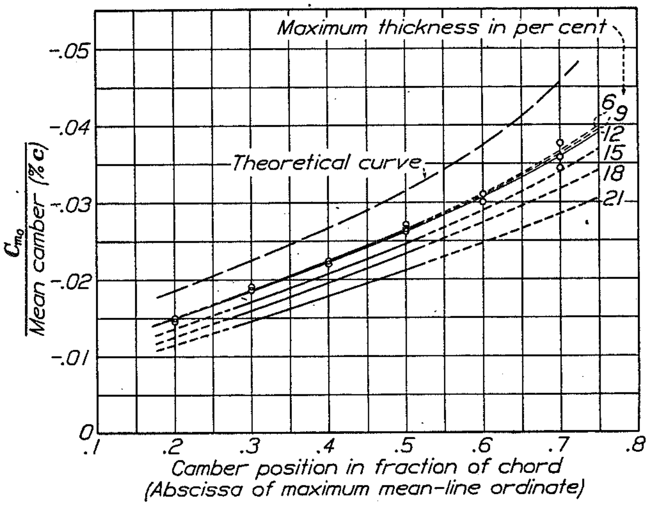


FIGURE 87.—Variation of moment at zero lift with camber. Points shown are for 12 percent thick airfoils. Curves indicate general trends for the different thicknesses.

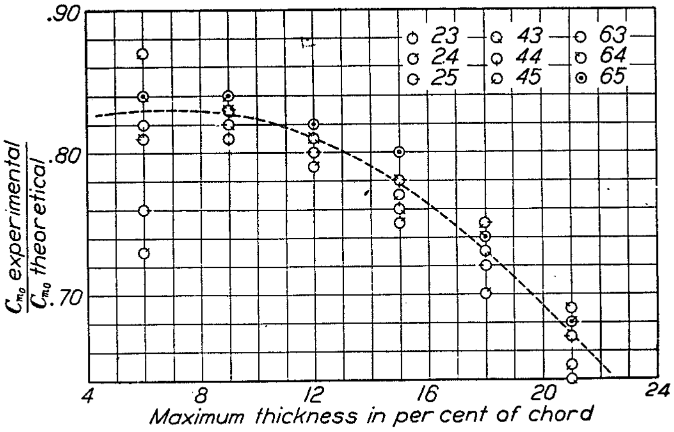


FIGURE 88.—Variation of moment at zero lift with thickness. Numbers refer to mean-camber designation.

As with the angle of zero lift, the theory states that the moment at zero lift is proportional to the camber and predicts an increase in the magnitude of the moment as the camber moves back along the chord. Figures 87 and 88 show the values of the moment coefficient as affected by variations of camber and thickness compared with the theoretical values. Referring to figure 87, the plotted data indicate that the moment coefficients are nearly proportional to the camber. It will also be noted that the curves representing the ratios of the experimental coefficients to the camber are nearly parallel to the equivalent curve representing the theoretical ratios except that the curves tend to diverge for positions of the camber well back. Figure 88 shows that the experimental values lie between 87 and 64 percent, approximately, of the theoretical. Numerical values of the moment coefficient at zero lift are given in table V.

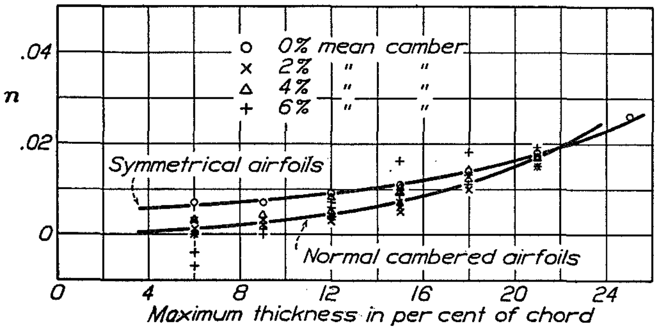


FIGURE 89.—Variation of position of constant moment with thickness. Values of n for equation $C_{m_{c/4}}=C_{m_0}+nC_L$. Results for airfoils having normal camber positions (0.3c to 0.5c).

If the resultant of the lift forces acted exactly through the quarter-chord point, as predicted by the theory of thin airfoils, there would be no additional moment due to the lift when the moments are taken about this point. The curves of $C_{m_{c/4}}$ against C_L, however, show a slope in the working range which indicates that the axis of constant moment is displaced somewhat from the quarter-chord point. The factor n represents the amount of this displacement as obtained from the deduced slopes of the moment curves in the normal working range. The variation of this displacement with thickness and with camber is shown in figures 89 and 90. Table VI gives the numerical values. Beyond the stall all the airfoils show a sharp increase in the magnitude of the pitching moment. The suddenness of this increase follows the degree of stability at the stall as indicated by the type of the lift-curve peak.

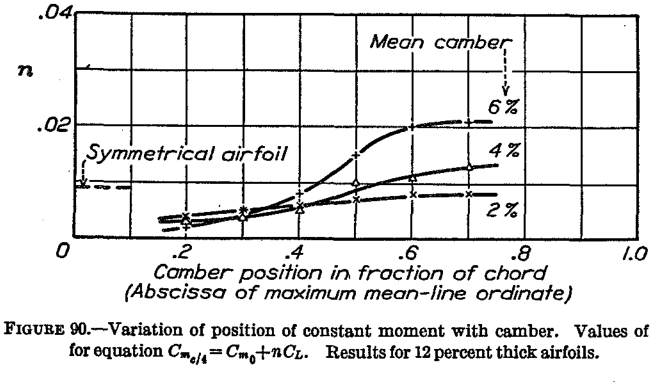


FIGURE 90.—Variation of position of constant moment with camber. Values of n for equation $C_{m_{c/4}}=C_{m_0}+nC_L$. Results for 12 percent thick airfoils.

DRAG

The total drag of an airfoil is considered as made up of the induced drag and the profile drag. Considering the profile drag as the minimum value plus an additional drag dependent upon the attitude of the airfoil, we have in coefficient form

$$C_D=C_{D_i}+(C_{D_{0min}}+\Delta C_{D_0})$$

The induced-drag coefficient C_{D_i}, which is computed by means of the formula given in reference 8, is considered to be independent of the airfoil section. The variation of the profile-drag coefficient with the shape variables of the airfoil section is analyzed with respect to the variations of the two components of the profile drag.

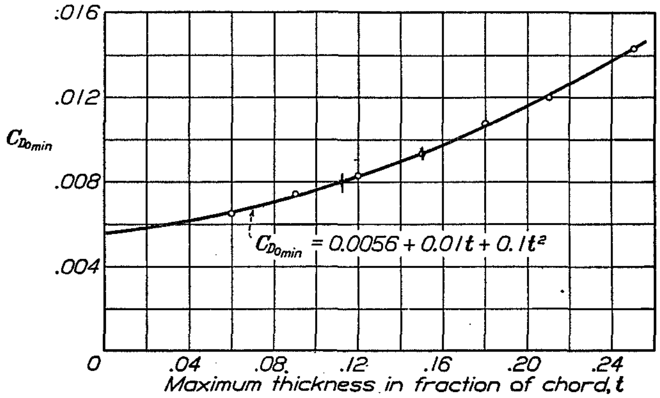


FIGURE 91.—Variation of minimum profile drag with thickness for the symmetrical airfoils.

Minimum profile drag.—The variation of the minimum profile-drag coefficient with thickness for the symmetrical sections is shown in figure 91. The cambered sections show the same general variation with thickness but, to avoid confusion, the results are not plotted. The variation of the minimum profile-drag coefficient with the profile thickness may be expressed by the empirical relation

$$C_{D_{0min}}=k+0.0056+0.01t+0.1t^2$$

where t is the thickness ratio and k (which is approximately constant for sections having the same mean line) represents the increase in $C_{D_{0min}}$ above that computed for the symmetrical section of corresponding thickness. The variation of $C_{D_{0min}}$ with camber is indicated by the variation of k as shown in figure 92.

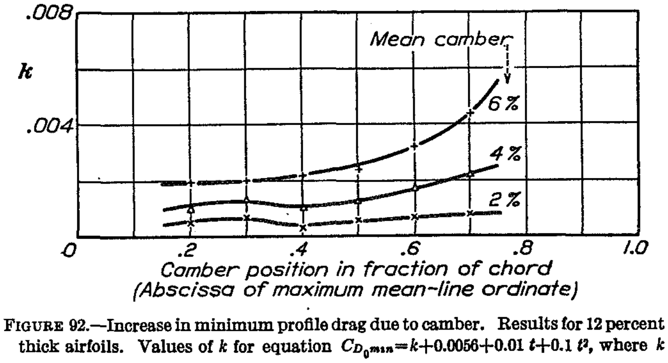


FIGURE 92.—Increase in minimum profile drag due to camber. Results for 12 percent thick airfoils. Values of k for equation $C_{D_{0min}}=k+0.0056+0.01t+0.1t^2$, where k is the increase in $C_{D_{0min}}$ due to camber and t is the maximum thickness in fraction of chord.

The effect of camber is small except for the highly cambered sections having the maximum camber well back. Numerical values of $C_{D_{0min}}$ are given in table VII.

Additional profile drag.—The additional profile drag, which is dependent upon the attitude of the airfoil, has previously been expressed as a function of the lift (reference 4) by the equation

$$\Delta C_{D_0}=C_{D_0}-C_{D_{0min}}=0.0062(C_L-C_{L_{opt}})^2$$

where $C_{L_{opt}}$ may be called the optimum lift coefficient; that is, the lift coefficient corresponding to the minimum profile-drag coefficient. This equation holds reasonably well for the normally shaped airfoils at values of the lift coefficient below unity.

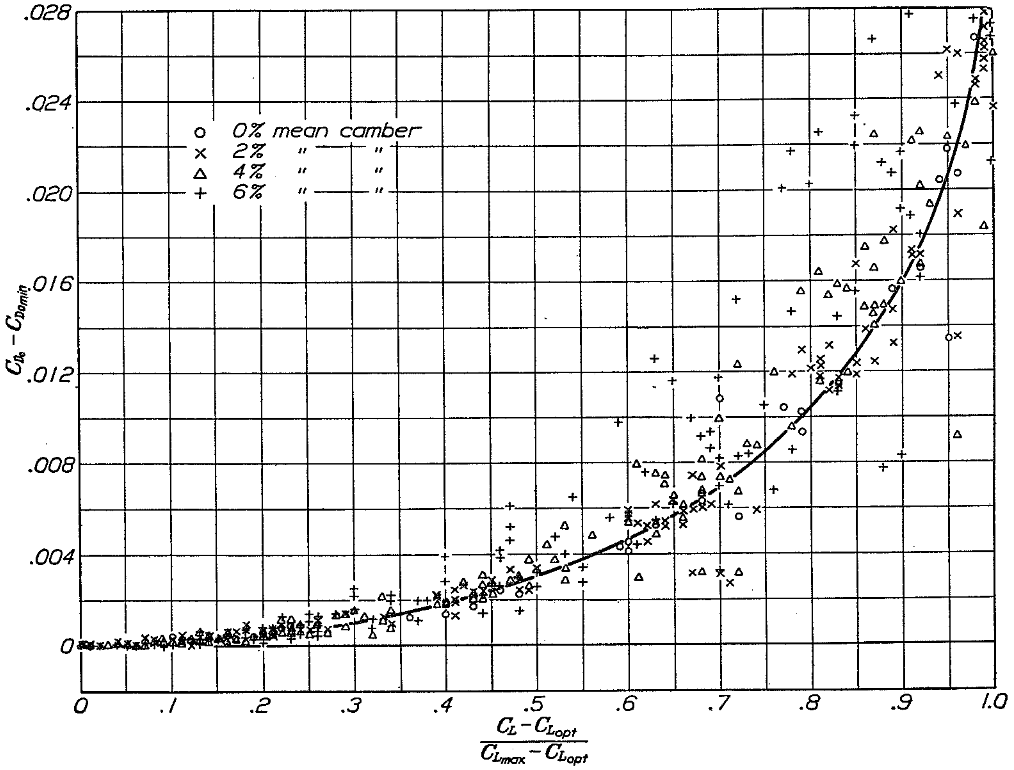


FIGURE 93.—Additional profile drag.

A convenient practical method of allowing for the increased values of C_{D_0} at moderately high values of the lift coefficient is to include the additional profile drag with the induced drag, as suggested in reference 2. For the symmetrical airfoils of moderate thickness the term to be added to the induced-drag coefficient was given as 0.0062 C_L^2. The relative importance of this term may be better appreciated by considering that it represents 11.7 percent of the induced drag of an elliptical airfoil of aspect ratio 6. The same method may also be applied to other airfoils if the value of the optimum lift is not too large.

Andrews (reference 14), using the part of these data published in references 2, 4, and 5, suggests for the additional profile drag the form

$$\Delta C_{D_0}=f\left(\frac{C_L-C_{L_{opt}}}{C_{L_{max}}-C_{L_{opt}}}\right)$$

This function is represented in figure 93 as the curve determined from the results for the symmetrical airfoils and for the airfoils having a camber of 2 percent of the chord. As the camber is increased, the dispersion of the plotted points from the curve becomes greater. In general the points above the curve correspond to thick sections and sections in which the maximum camber is well back. The departure from the curve becomes greater with increased thickness and with a rearward movement of the maximum-camber position. The points well below the curve correspond to the thin airfoils.

Because the additional profile drag is not a simple function of the lift, and also because the results as presented in figure 93 are difficult to follow, generalized curves for the relation

$$\Delta C_{D_0}=f(C_L-C_{L_{opt}})$$

are given in figure 94. These curves are given to represent more accurately the additional profile drag for the normally shaped sections.

Optimum lift.—The optimum lift, as defined above, is the value of the lift corresponding to the minimum profile drag. As the determination of this value of the lift is largely dependent upon the fairing of the profile-drag curves, special curves were faired for this purpose on enlarged-scale plots corresponding to certain related airfoils grouped together. The values of the optimum lift coefficients obtained in this manner are given in table VIII. It may be noted by reference to this table that the optimum lift coefficient increases with camber and for the highly cambered sections a definite increase accompanies a forward movement of the camber.

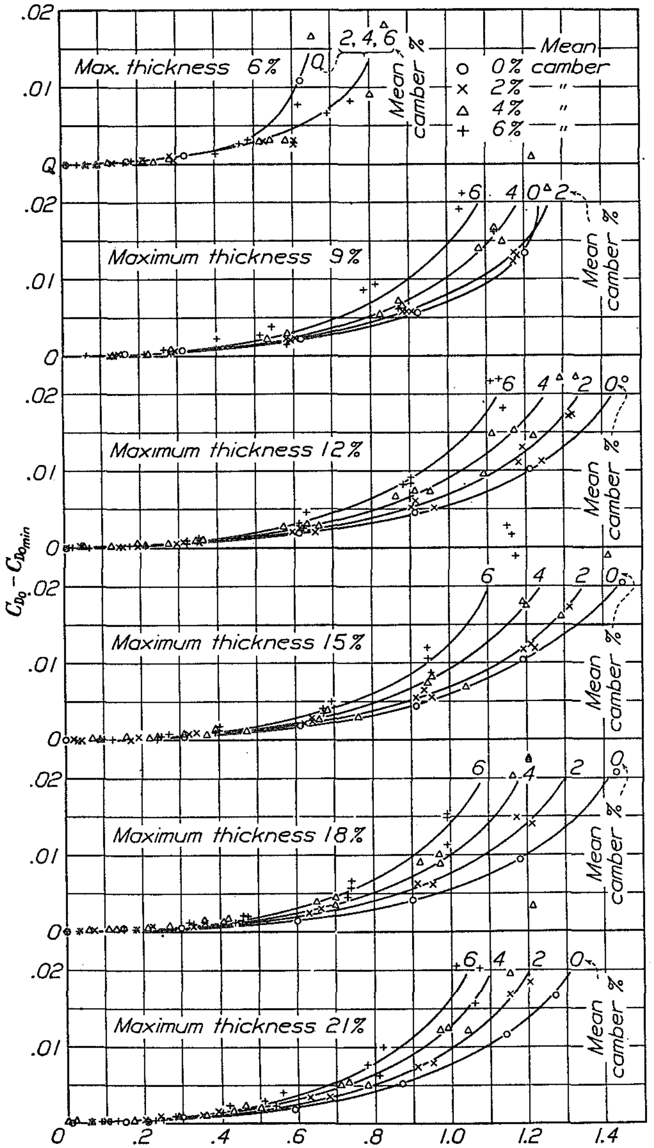


FIGURE 94.—Additional profile drag as a function of $C_L - C_{L_{opt}}$. Results are for airfoils having normal camber positions (0.3c to 0.5c).

More important than these variations, however, is the variation with thickness. The rapid decrease in the optimum lift with increased thickness indicates that it is not primarily dependent upon the shape of the mean line. Nevertheless it is interesting to compare the optimum lift coefficients with the values included in table VIII representing the theoretical lift coefficients at the "ideal" angle of attack for the mean line; i.e., the angle of attack for which the thin-airfoil theory gives a finite velocity at the nose. (See the appendix.)

GENERAL EFFICIENCY

The general efficiency of an airfoil cannot be expressed by means of a single number. The ratio of the maximum lift to the minimum profile drag is, however, of some value as the measure of the efficiency of an airfoil section. The variation of this ratio with thickness is shown in figure 95. The curves of this figure indicate that the highest values of the ratio are given by the sections between 9 and 12 percent of the chord thick. The variation with camber, shown in figure 96, is less important. An increase in the camber

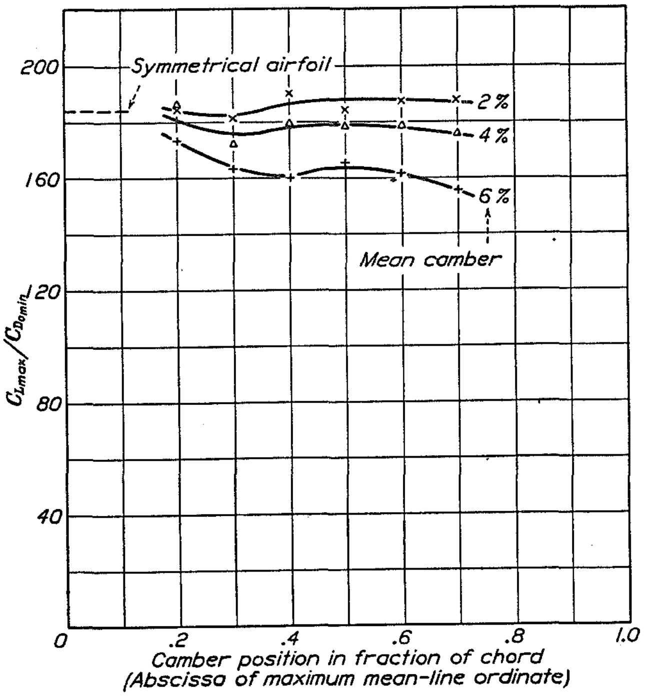


FIGURE 96.—Variation of $C_{L_{max}}/C_{D_{0_{min}}}$ with camber. Results are for 12 percent thick airfoils.

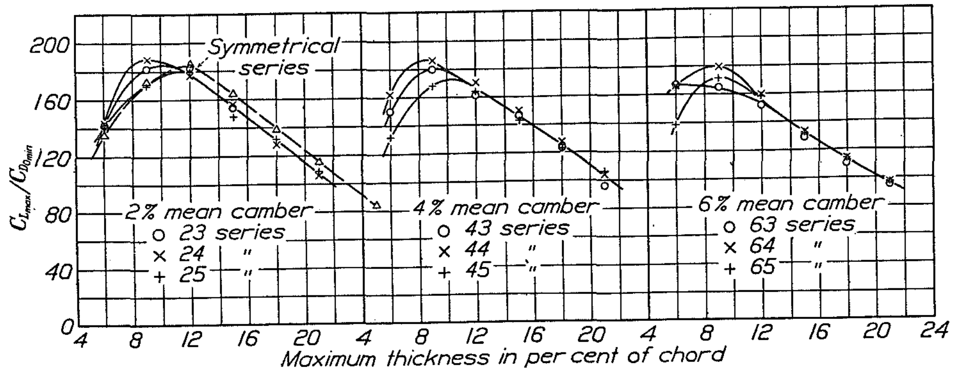


FIGURE 95.—Variation of $C_{L_{max}}/C_{D_{0_{min}}}$ with thickness.

above 2 percent of the chord and a rearward movement of the camber (for the highly cambered sections) tend to decrease the value of $C_{L_{max}}/C_{D_{0min}}$. The numerical values of the ratio are given in table IX.

SUPPLEMENTARY AIRFOILS

For the purpose of investigating briefly the effects of certain shape variables other than those discussed in the main body of the report, 10 supplementary airfoils were tested. The airfoil sections were as follows: 6 symmetrical sections with modified nose shapes, 2 sections with reflexed mean lines, and 2 sections simulating those of a wing having a flexible trailing edge.

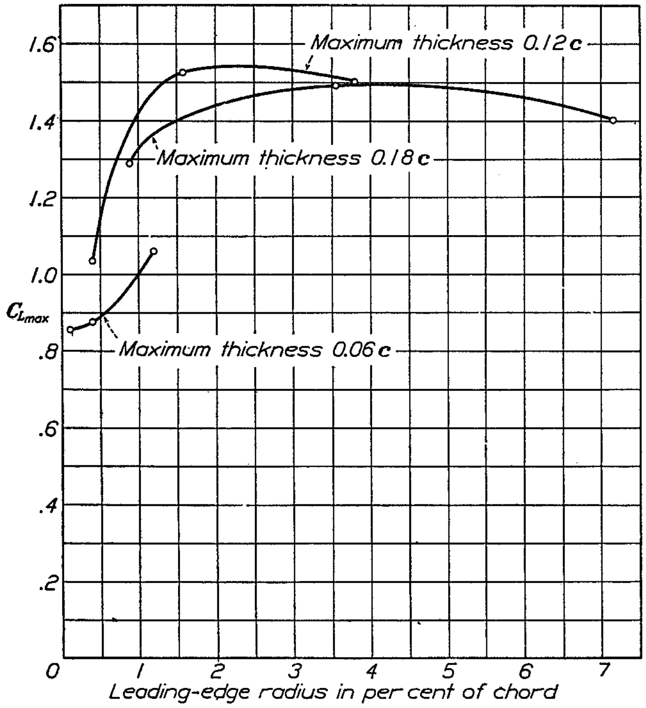


FIGURE 97.—Variation of maximum lift with nose radius.

Airfoils with modified nose shapes.—The airfoils of the first supplementary group investigated were developed from three of the symmetrical N.A.C.A. family airfoils: The N.A.C.A. 0006, the N.A.C.A. 0012, and the N.A.C.A. 0018. For each of these basic (or normal) sections one thinner-nosed section, denoted by the suffix T, and one blunter-nosed section, denoted by the suffix B, were developed and tested. The derivation of each modified section was similar to that of the normal section and was accomplished by a systematic change in the equation that defines the normal section. This change is principally a change in the nose radius, but it also results in modifications to the profile throughout its length, except at the maximum ordinate and at the trailing edge. The nose radii of the sections in percent of the chord are as follows:

Section	T series	Normal	B series
0006	0.10	0.39	1.19
0012	.40	1.58	3.80
0018	.89	3.55	7.15

The aerodynamic characteristics of the modified sections are given in figures 72 to 77. These may be compared with the characteristics of the normal sections given in figures 4, 6, and 8. The maximum lift coefficients of the modified and the normal sections are plotted against the leading-edge radii in figure 97. It is interesting to note that the leading-edge radius is very critical in its effect on the maximum lift when the radius is small. This critical effect is also indicated by the rapid increase in the maximum lift with increasing thickness for the thin sections as shown in figure 85.

Airfoils with reflexed mean lines.—Previous investigations have shown that the pitching moment of cambered airfoils can be reduced by altering the form of the mean line toward the trailing edge, with a consequent loss of maximum lift but only a small reduction in drag. In order to compare the characteristics of sections of this type with those of the related sections of normal form, two airfoils were developed with the basic thickness distribution of the N.A.C.A. 0012 disposed about certain mean lines of the form given in reference 15

$$y_c = hx(1-x)\ (1-\lambda x)$$

The values of h in this equation were chosen to give a camber of 0.02 and the values of λ were chosen to give the airfoil designated the N.A.C.A. $2R_112$ a small negative moment and the airfoil designated the N.A.C.A. $2R_212$ a small positive moment. Characteristic curves for the two airfoils are given in figures 77 and 78. The principal characteristics of the sections may be conveniently compared with those of the related symmetrical section, the N.A.C.A. 0012, and a related normal section having a camber of 2 percent of the chord, the N.A.C.A. 2412, by means of the following table arranged in the order of increasing pitching-moment coefficients.

Section	$C_{L_{max}}$	$C_{D_{0min}}$	$\frac{C_{L_{max}}}{C_{D_{0min}}}$	C_{m_0}
$2R_212$	1.47	0.0086	171	0.004
0012	1.53	.0083	184	−.002
$2R_112$	1.53	.0083	184	−.020
2412	1.62	.0085	190	−.044

These results indicate that airfoils having reflexed mean lines may be of questionable value because of the adverse effect of this mean-line shape on the maximum lift coefficient.

Thickness and camber modifications near the trailing edge.—Two airfoils were developed to simulate an airfoil having a flexible trailing edge in a straight and in a given deflected position. The thickness distribution is composed of three parts: the forward portion (0 to 0.3*c*) having the same distribution as the N.A.C.A. 0012, the rear portion (from 0.7*c* to the trailing edge) having a thin, uniform value, and the central portion joining these two with fair curves. As shown in figure 80, the two airfoils differ only in the rear portion, the section designated N.A.C.A. 0012F_0 simulating that of a wing having the trailing edge deformed for the high-speed condition, and the section designated N.A.C.A. 0012F_1 simulating that of the same wing with the trailing edge bent down in a circular arc. Curves of the aerodynamic characteristics for both conditions are compared in figure 80. Considering the results given by both airfoils as two conditions for one airfoil, a very high maximum lift with a reasonably low minimum drag is obtained. On this assumption the ratio $\frac{C_{L_{max}}}{C_{D_{0_{min}}}}$ is 197, slightly higher than the value of this ratio given by the N.A.C.A. 2412.

In order to study the effects of an extreme change in the thickness distribution, the principal characteristics of the two sections may be compared with those of the related normal sections, the N.A.C.A. 0012 and the N.A.C.A. 6712. The maximum lift coefficient is little affected by the change in the thickness distribution, but it is of interest to note (table I) that the slope of the lift curve of the N.A.C.A. 0012F_0 is slightly greater than 2π per radian, as compared with an appreciably lower slope for the N.A.C.A. 0012. The profile drag is also affected by the change in the thickness distribution. Of the two symmetrical sections, the profile drag of the N.A.C.A. 0012F_0 is much higher than that of the N.A.C.A. 0012 over the entire lift range. This is not true, however, for the two cambered sections. Comparing the characteristics of the N.A.C.A. 0012F_1 with those of the N.A.C.A. 6712, we find that at low values of the lift the profile drag of the former is much higher, but as the lift increases this difference becomes less, and in the high-lift range the profile drag of the N.A.C.A. 0012F_1 is considerably less than that of the N.A.C.A. 6712.

CONCLUSIONS

The variation of the aerodynamic characteristics of the related airfoils with the geometric characteristics investigated may be summarized as follows:

Variation with thickness ratio:

1. The slope of the lift curve in the normal working range decreases with increased thickness, varying from 95 to 81 percent, approximately, of the theoretical slope for thin airfoils (2π per radian).
2. The angle of zero lift moves toward zero with increased thickness (above 9 to 12 percent of the chord thickness ratios).
3. The highest values of the maximum lift are obtained with sections of normal thickness ratios (9 to 15 percent).
4. The greatest instability of the air flow at maximum lift is encountered with the moderately thick, low-cambered sections.
5. The magnitude of the moment at zero lift decreases with increased thickness, varying from 87 to 64 percent, approximately (for normally shaped airfoils), of the values obtained by thin-airfoil theory.
6. The axis of constant moment usually passes slightly forward of the quarter-chord point, the displacement increasing with increased thickness.
7. The minimum profile drag varies with thickness approximately in accordance with the expression

$$C_{D_{0_{min}}} = k + 0.0056 + 0.01t + 0.1t^2$$

where the value of *k* depends upon the camber and *t* is the ratio of the maximum thickness to the chord.

8. The optimum lift coefficient (the lift coefficient corresponding to the minimum profile-drag coefficient) approaches zero as the thickness is increased.
9. The ratio of the maximum lift to the minimum profile drag is highest for airfoils of medium thickness ratios (9 to 12 percent).

Variation with camber:

1. The slope of the lift curve in the normal working range is little affected by the camber; a slight decrease in the slope is indicated as the position of the camber moves back.
2. The angle of zero lift is between 100 and 75 percent, approximately, of the value given by thin-airfoil theory, the smaller departures being for airfoils with the normal camber positions.
3. The maximum lift increases with increased camber, the increase being more rapid as the camber moves forward or back from a point near the 0.3*c* position.
4. Greater stability of the air flow at maximum lift is obtained with increased camber if the camber is in the normal positions (0.3*c* to 0.5*c*).
5. The moment at zero lift is nearly proportional to the camber. For any given thickness, the difference between the experimental value of the constant of proportionality and the value predicted by thin-airfoil theory is not appreciably affected by the position of the camber except for the sections having the maximum camber well back, where the difference becomes slightly greater.
6. The axis of constant moment moves forward as the camber moves back.
7. The minimum profile drag increases with increased camber, and also with a rearward movement of the camber.

8. The optimum lift coefficient increases with the camber and for the highly cambered sections a definite increase accompanies a forward movement of the camber.

9. The ratio of the maximum lift to the minimum profile drag tends to decrease with increased camber (above 2 percent of the chord) and with a rearward movement of the camber (for the highly cambered sections).

LANGLEY MEMORIAL AERONAUTICAL LABRATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *December 20, 1932.*

APPENDIX

It is proposed in this section of the report to present, briefly, a summary of the results of the existing thin-airfoil theory (based on the section mean line) as applied to the prediction of certain section characteristics. Such a summary is desirable because at present the results must be obtained from several different sources which give them in a form not easily applied. Three characteristics are considered; namely, (1) the angle of zero lift α_{L_0}, (2) the pitching-moment coefficient $C_{m_{c/4}}$, and (3) the "ideal" angle of attack α_I, or the corresponding lift coefficient C_{L_I}, that is, values corresponding to the unique condition for which the theory gives a finite velocity at the nose of the airfoil. (See reference 16.)

Expressions for lift and moment coefficients may be written as follows if the angles are measured in radians:

$$C_L = 2\pi(\alpha - \alpha_{L_0}) \tag{1}$$

$$C_{L_1} = 2\pi(\alpha_I - \alpha_{L_0}) \tag{2}$$

$$C_{m_c/4} = \frac{\pi}{2}(\beta + \alpha_{L_0}) \tag{3}$$

If the leading end of the mean line is chosen as the origin of coordinates and the trailing end is taken on the x axis at $x=1$, then the parameters α_{L0}, α_I, and β are given by the following integrals

$$\alpha_{L_0} = \int_0^1 y\, \mathrm{f}_1(x)\, dx \tag{4}$$

$$\alpha_I = \int_0^1 y\, \mathrm{f}_2(x)\, dx \tag{5}$$

$$\beta = \int_0^1 y\, \mathrm{f}_3(x)\, dx \tag{6}$$

where

$$\mathrm{f}_1(x) = \frac{-1}{\pi(1-x)\,[x(1-x)]^{1/2}} \tag{7}$$

$$\mathrm{f}_2(x) = \frac{(1-2x)}{2\pi[x(1-x)]^{3/2}} \tag{8}$$

$$\mathrm{f}_3(x) = \frac{4(1-2x)}{\pi[x(1-x)]^{1/2}} \tag{9}$$

and y is the ordinate of the mean line at a given abscissa x. The integrals (4) and (6) may be shown to be identical with the corresponding integrals given by Glauert (reference 15) and by Munk (reference 17), and integral (5) is given by Theodorsen (reference 16).

The evaluation of these integrals for the N.A.C.A. airfoil sections given in this report was accomplished analytically. The values of α_{L_0} (changed from radians to degrees), $C_{m_{c/4}}$ and C_{L_I}, so computed, are given in tables III, IV, and VII, respectively, in the main body of the report. This method of evaluation, however, cannot be applied to many of the commonly used sections because they do not have analytically defined mean lines; hence, an approximate method must be used. A graphical determination gives good results and for convenience the values of the three functions, (7), (8), and (9), at several values of x, are given in the following table:

x	$\mathrm{f}_1(x)$	$\mathrm{f}_2(x)$	$\mathrm{f}_3(x)$	x	$\mathrm{f}_1(x)$	$\mathrm{f}_2(x)$	$\mathrm{f}_3(x)$
0	$-\infty$	∞	∞	0.30	−0.992	0.662	1.111
0.0125	−2.901	113.15	11.17	.40	−1.083	.271	.520
.0250	−2.091	39.73	7.747	.50	−1.273	0	.0
.0500	−1.537	13.84	5.258	.60	−1.624	−.271	−.520
.0750	−1.306	7.403	4.109	.70	−2.315	−.662	−1.111
.1000	−1.179	4.716	3.395	.80	−3.979	−1.492	−1.910
.15	−1.049	2.447	2.496	.90	−10.61	−4.716	−3.395
.20	−.995	1.492	1.910	.95	−29.21	−13.84	−5.258
.25	−.980	.980	1.470	1.00	$-\infty$	$-\infty$	$-\infty$

In general, some difficulty would be expected with the graphical method because the values of the above functions tend to infinity at the leading and trailing edges. Actually, because the ordinates of the mean-line extremities are zero, the integrand may approach zero, and does at the leading edge for the integral (4), and at the leading and trailing edges for the integral (6). Difficulty, however, is encountered at the trailing edge for the integral (4) and at the leading and trailing edges for the integral (5). In order to avoid this difficulty, integral (4) is evaluated graphically from $x=0$ to $x=0.95$, and the increment contributed by the portion from $x=0.95$ to $x=1$ is determined analytically. Likewise, integral (5) is evaluated graphically from $x=0.05$ to $x=0.95$ and analytically for the extremities. The analytical determination of the increments is accomplished by assuming the mean line near the ends to be of the form

$$y = a + bx + cx^2$$

Evaluating the integrals gives

$$\Delta\alpha_{L_0} = \quad -0.964y_{0.95} + 0.0954y'_1 \qquad (x=0.95 \text{ to } x=1)$$

$$\Delta\alpha_I = \begin{cases} +0.467y_{0.05} + 0.0472y'_0 & (x=0 \text{ to } x=0.05) \\ -0.467y_{0.95} + 0.0472y'_1 & (x=0.95 \text{ to } x=1) \end{cases}$$

where y'_0 and y'_1 are the mean-line slopes at the leading and trailing edges, respectively.

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TABLE I.—IMPORTANT CHARACTERISTICS

Airfoil	Page	Section characteristics							Wing characteristics A.R. 6			Thickness at		*c.p.* at		[4]$(C/B)_0$
		$C_{L_{max}}$	α_0 at $C_{L_{max}}$ (deg.)	α_{L_0} (deg.)	$a_0=\frac{dC_L}{d\alpha_0}$ (per deg.)	$C_{D_{0_{min}}}$	$\frac{C_{L_{max}}}{C_{D_{0_{min}}}}$	C_{m_0}	$C_{D_{min}}$	$(L/D)_{max}$	C_L at $(L/D)_{max}$	0.15 chord	0.65 chord	Maximum forward position	¼ $C_{L_{max}}$	
												Percent chord		Percent chord		
0006	7	0.88	13	−0.1	0.102	0.0065	135	−0.002	0.0065	23.8	0.31	5.35	4.13	25	25	−0.082
0009	7	1.27	14	.0	.101	.0074	172	−.003	.0074	22.9	.36	8.02	6.20	25	25	−.213
0012	8	1.53	17	.0	.101	.0083	184	−.002	.0083	22.2	.37	10.69	8.27	[1] 25	25	−.285
0015	8	1.53	17	.0	.100	.0093	164	.000	.0093	21.2	.40	13.36	10.33	[1] 25	24	−.279
0018	9	1.49	17	.0	.098	.0108	138	−.002	.0108	19.8	.40	16.04	12.40	24	24	−.285
0021	9	1.38	17	−.1	.094	.0120	115	−.001	.0120	18.5	.44	18.71	14.46	23	23	−.270
0025	10	1.20	16	.0	.089	.0143	84	−.003	.0143	16.5	.47	22.27	17.22	23	23	−.233
2212	10	1.60	16	−1.8	.103	.0087	184	−.029	.0088	22.4	.40	10.69	8.25	27	32	−.262
2306	11	1.04	11	−1.8	.104	.0073	142	−.036	.0075	23.9	.33	5.36	4.14	29	38	−.130
2309	11	1.51	15	−2.0	.103	.0083	182	−.036	.0085	22.9	.39	8.04	6.21	28	34	−.236
2312	12	1.61	16	−1.9	.101	.0089	181	−.038	.0090	22.1	.39	10.71	8.27	27	34	−.268
2315	12	1.54	15	−1.7	.102	.0100	154	−.034	.0100	20.5	.41	13.38	10.36	27	34	−.251
2406	13	1.01	13	−1.7	.103	.0070	144	−.039	.0074	24.9	.32	5.34	4.14	29	40	−.103
2409	13	1.51	14	−1.7	.103	.0080	189	−.044	.0082	23.1	.36	8.02	6.20	28	36	−.242
2412	14	1.62	17	−1.8	.101	.0085	190	−.044	.0087	22.5	.39	10.71	8.27	28	35	−.274
2415	14	1.55	16	−1.7	.101	.0099	156	−.040	.0100	20.8	.40	13.39	10.34	28	35	−.262
2418	15	1.43	15	−1.9	.098	.0112	128	−.037	.0113	19.4	.42	16.08	12.39	27	34	−.238
2421	15	1.35	16	−1.7	.097	.0127	106	−.036	.0128	17.9	.43	18.75	14.46	27	34	−.229
2506	16	1.03	15	−2.0	.103	.0073	141	−.048	.0076	24.2	.36	5.36	4.13	30	44	−.116
2509	16	1.38	13	−2.0	.102	.0081	170	−.052	.0083	22.9	.37	8.04	6.21	29	40	−.207
2512	17	1.62	17	−2.1	.102	.0088	184	−.054	.0091	22.3	.39	10.70	8.27	28	37	−.270
2515	17	1.53	16	−2.0	.099	.0103	148	−.049	.0104	20.4	.41	13.38	10.33	28	37	−.255
2518	18	1.48	16	−2.0	.096	.0112	132	−.047	.0113	19.1	.42	16.07	12.41	28	36	−.255
2521	18	1.38	16	−1.8	.095	.0126	109	−.043	.0126	17.7	.44	18.72	14.47	28	36	−.233
2612	19	1.66	17	−2.3	.100	.0089	187	−.060	.0091	22.1	.38	10.70	8.26	28	38	−.274
2712	19	1.68	17	−2.6	.100	.0090	187	−.075	.0093	22.0	.38	10.69	8.25	29	41	−.272
4212	20	1.71	16	−3.4	.102	.0092	186	−.059	.0100	22.1	.40	10.70	8.27	29	38	−.260
4306	20	1.20	10	−3.8	.103	.0080	150	−.075	.0094	23.7	.38	5.40	4.14	31	49	−.141
4309	21	1.60	15	−3.6	.103	.0089	180	−.073	.0094	22.3	.39	8.09	6.21	29	43	−.236
4312	21	1.63	16	−3.9	.100	.0095	172	−.075	.0100	21.7	.40	10.77	8.27	30	43	−.236
4315	22	1.56	15	−3.6	.103	.0107	146	−.068	.0108	20.2	.42	13.47	10.34	29	42	−.233
4318	22	1.46	14	−3.5	.099	.0119	123	−.065	.0121	19.0	.43	16.14	12.41	29	41	−.225
4321	23	1.29	15	−3.6	.095	.0134	96	−.057	.0134	17.4	.45	18.81	14.46	29	41	−.196
4406	23	1.23	10	−3.9	.104	.0076	162	−.087	.0089	24.2	.38	5.40	4.16	32	53	−.144
4409	24	1.60	15	−3.6	.103	.0086	186	−.086	.0092	22.9	.40	8.07	6.21	31	46	−.242
4412	24	1.65	16	−3.9	.100	.0092	179	−.089	.0096	22.1	.40	10.77	8.28	31	45	−.253
4415	25	1.57	15	−3.8	.101	.0105	150	−.083	.0108	20.5	.42	13.45	10.34	30	45	−.242
4418	25	1.47	17	−3.7	.096	.0116	127	−.078	.0120	19.2	.43	16.15	12.40	30	44	−.231
4421	26	1.37	19	−3.4	.093	.0132	104	−.071	.0133	17.7	.44	18.79	14.48	30	44	−.222
4506	26	1.15	13	−4.3	.104	.0087	132	−.109	.0098	22.7	.40	5.38	4.14	33	63	−.103
4509	27	1.56	13	−4.1	.103	.0093	168	−.106	.0099	22.0	.40	8.08	6.21	32	52	−.229
4512	27	1.69	17	−4.2	.097	.0095	178	−.105	.0099	21.7	.40	10.74	8.28	31	49	−.262
4515	28	1.62	17	−4.1	.101	.0113	143	−.097	.0116	19.6	.43	13.44	10.35	31	48	−.253
4518	28	1.54	17	−3.9	.096	.0125	123	−.094	.0126	18.4	.43	16.14	12.41	31	48	−.244
4521	29	1.46	19	−3.4	.095	.0138	106	−.082	.0138	17.2	.45	18.80	14.47	30	46	−.244
4612	29	1.76	17	−4.6	.098	.0099	178	−.124	.0105	21.1	.41	10.73	8.27	31	52	−.275
4712	30	1.82	18	−5.0	.097	.0104	175	−.143	.0110	20.7	.41	10.74	8.26	32	55	−.290
6212	30	1.75	14	−5.2	.100	.0101	173	[3]−.087	.0117	20.9	.44	10.78	8.29	30	44	−.240
6306	31	1.54	12	[2]−5.2	.105	.0092	167	[3]−.109	.0177	21.6	.42	5.47	4.15	32	54	−.187
6309	31	1.67	13	−5.4	.104	.0101	165	−.110	.0116	21.1	.42	8.18	6.23	32	51	−.213
6312	32	1.66	14	−5.5	.101	.0102	163	−.110	.0115	20.9	.44	10.86	8.29	31	51	−.218
6315	32	1.55	13	−5.4	.101	.0120	129	−.105	.0125	19.3	.45	13.58	10.37	32	52	−.214
6318	33	1.43	13	−5.2	.098	.0130	110	−.097	.0133	18.4	.45	16.27	12.44	32	50	−.209
6321	33	1.37	17	−5.2	.096	.0144	95	−.090	.0145	17.0	.47	18.92	14.51	31	50	−.214
6406	34	1.43	9	−5.6	.104	.0086	166	[3]−.129	.0139	22.6	.42	5.42	4.15	34	62	−.157
6409	34	1.68	15	−5.9	.101	.0094	179	−.133	.0113	21.6	.42	8.14	6.21	33	57	−.225
6412	35	1.67	15	−5.7	.101	.0104	160	−.132	.0117	20.8	.42	10.85	8.29	33	56	−.242
4415	35	1.59	17	−5.7	.099	.0120	133	−.125	.0127	19.2	.45	13.55	10.36	33	56	−.238
6418	36	1.51	18	−5.7	.099	.0132	114	−.118	.0137	18.1	.45	16.28	12.43	33	55	−.231
6421	36	1.41	18	−5.2	.096	.0146	97	−.110	.0148	16.9	.46	18.96	14.50	33	54	−.224
6506	37	1.29	10	[2]−6.3	.101	.0093	139	[3]−.159	.0122	21.6	.42	5.41	4.14	35	74	−.121
6509	37	1.71	15	−6.3	.103	.0100	171	−.158	.0119	21.0	.43	8.14	6.21	34	62	−.236
6512	38	1.75	17	−6.2	.101	.0106	165	[3]−.159	.0119	20.6	.42	10.84	8.30	33	60	−.257
6515	38	1.67	18	−6.0	.099	.0127	132	[3]−.150	.0134	18.7	.44	13.53	10.36	33	59	−.253
6518	39	1.61	18	−5.7	.095	.0141	114	−.139	.0142	17.4	.46	16.22	12.44	33	58	−.251
6521	39	1.49	19	−5.3	.094	.0154	97	−.129	.0155	16.0	.47	18.92	14.49	33	57	−.233
6612	40	1.83	17	−6.6	.099	.0114	161	[3]−.186	.0124	19.8	.43	10.80	8.28	33	64	−.270
6712	40	1.95	18	−7.0	.097	.0126	155	[3]−.206	.0135	18.6	.45	10.76	8.27	34	65	−.289
0006T	41	.85	13	−.1	.100	.0069	123	.005	.0069	18.7	.23	5.09	3.84	[1] 24	21	−.028
0006B	41	1.06	11	.0	.104	.0076	139	.005	.0076	22.5	.34	5.74	4.57	[1] 24	22	−.162
0012T	42	1.03	12	−.1	.099	.0082	126	.001	.0082	21.5	.36	10.19	7.68	[1] 25	24	−.178
0012B	42	1.50	16	.0	.101	.0095	158	.000	.0095	20.8	.40	11.48	9.13	[1] 24	23	−.275
0018T	43	1.29	15	.1	.098	.0102	127	.000	.0102	19.3	.41	15.28	11.52	[1] 25.	24	−.238
0018B	43	1.40	16	.0	.097	.0122	115	.001	.0122	18.2	.44	17.23	13.70	[1] 23	22	−.272
2R$_1$12	44	1.53	16	−1.5	.101	.0083	184	−.020	.0086	22.8	.38	10.70	8.26	26	29	−.264
2R$_2$12	44	1.47	16	−.6	.102	.0086	171	.004	.0087	22.2	.38	10.71	8.25	[1] 25	23	−.257
0012F$_0$	45	1.53	15	−.2	.111	.0104	147	.000	.0104	19.5	.42	10.70	--------	[1] 26	25	−.238
0012F$_1$	45	2.05	12	−11.7	.099	.0139	147	−.199	.0184	17.6	.55	10.70	--------	34	68	−.189

---

[1] Based on ¾ $C_{L_{max}}$.

[2] Based on straight portion of lift curve extended. See curve for actual value.

[3] Based on straight portion of moment curve extended. See curve for actual value.

[4] Ratio of the chord component to the beam component of the air forces to be used for the high angle of attack condition if the plane of the drag truss is parallel to the airfoil chord. *C/B* should be calculated when the plane of the drag truss is not parallel to the chord.

$$C/B=\tan\left[\tan^{-1}(C/B)_0-i_t\right] \quad \text{or} \quad C/B=\frac{(C/B)_0+k}{1-k\,(C/B)_0}$$

where i_t is the angle of incidence of the drag truss with respect to the airfoil chord.

where k is the slope of the drag truss with respect to the airfoil chord.

TABLE II.—SLOPE OF LIFT CURVE, $a_0=\frac{dC_L}{d\alpha_0}$ (PER DEG.)

Camber designation \ Thickness designation	06	09	12	15	18	21	25	[1]12
00	0.102	0.101	0.101	0.100	0.098	0.094	0.089	0.101
22								.103
23	.104	.103	.102	.102				.101
24	.103	.103	.103	.101	.098	.097		.101
25	.103	.102	.102	.099	.096	.095		.102
26								.100
27								.100
42								.102
43	.103	.103	.102	.103	.099	.095		.100
44	.104	.103	.100	.101	.096	.093		.100
45	.104	.103	.101	.101	.096	.095		.097
46								.098
47								.097
62								.100
63	.105	.104	.102	.101	.098	.096		.101
64	.104	.101	.102	.099	.099	.096		.101
65	.101	.103	.101	.099	.095	.094		.101
66								.099
67								.097

[1] *Additional tests to determine variation with camber.*

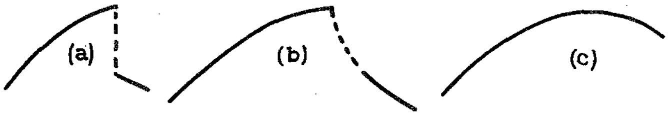
TABLE III.—ANGLE OF ZERO LIFT, α_{L_0} (DEGREES)

Camber designation \ Thickness designation	06	09	12	15	18	21	25	12	Theor.
00	−0.1	0.0	0.0	0.0	0.0	−0.1	0.0	0.0	0
22								−1.8	−1.80
23	−1.8	−2.0	−1.7	−1.7				−1.9	−1.92
24	−1.7	−1.7	−1.7	−1.7	−1.9	−1.7		−1.8	−2.08
25	−2.0	−2.0	−2.0	−2.0	−2.0	−1.8		−2.1	−2.29
26								−2.3	−2.59
27								−2.6	−3.04
42								−3.4	−3.60
43	−3.8	−3.6	−3.7	−3.6	−3.5	−3.6		−3.9	−3.84
44	−3.9	−3.6	−3.9	−3.8	−3.7	−3.4		−3.9	−4.15
45	−4.3	−4.1	−4.0	−4.1	−3.9	−3.4		−4.2	−4.58
46								−4.6	−5.18
47								−5.0	−6.09
62								−5.2	−5.40
63	[1]−5.2	−5.4	−5.4	−5.4	−5.2	−5.2		−5.5	−5.75
64	−5.6	−5.9	−5.7	−5.7	−5.7	−5.2		−5.7	−6.23
65	[1]−6.3	−6.3	−6.3	−6.0	−5.7	−5.3		−6.2	−6.88
66								−6.6	−7.78
67								−7.0	−9.13

[1] Based on straight portion of lift curve extended. See curve for actual value.

TABLE IV.—MAXIMUM LIFT COEFFICIENT, $C_{L_{max}}$

Camber designation \ Thickness designation	06	09	12	15	18	21	25	12
00	^{c}0.88	^{b}1.27	^{a}1.53	^{b}1.53	^{b}1.49	^{a}1.38	^{b}1.20	^{a}1.53
22								^{b}1.60
23	^{c}1.04	^{a}1.51	^{b}1.60	^{b}1.54				^{b}1.61
24	^{c}1.01	^{b}1.51	^{b}1.59	^{b}1.55	^{b}1.43	^{c}1.35		^{b}1.62
25	^{c}1.03	^{c}1.38	^{b}1.60	^{b}1.53	^{c}1.48	^{b}1.38		^{b}1.62
26								^{b}1.66
27								^{b}1.68
42								^{a}1.71
43	^{c}1.20	^{b}1.60	^{b}1.63	^{b}1.56	^{b}1.46	^{c}1.29		^{b}1.63
44	^{c}1.23	^{b}1.60	^{c}1.61	^{c}1.57	^{c}1.47	^{c}1.37		^{c}1.65
45	^{c}1.15	^{c}1.56	^{b}1.69	^{c}1.62	^{c}1.54	^{c}1.46		^{b}1.69
46								^{b}1.76
47								^{a}1.82
62								^{b}1.75
63	^{a}1.54	^{b}1.67	^{b}1.64	^{b}1.55	^{c}1.43	^{c}1.37		^{b}1.66
64	^{a}1.43	^{c}1.68	^{c}1.65	^{c}1.59	^{c}1.51	^{c}1.41		^{c}1.67
65	^{c}1.29	^{c}1.71	^{c}1.75	^{c}1.67	^{c}1.61	^{c}1.49		^{c}1.75
66								^{c}1.83
67								^{a}1.95



NOTE.—Letter indicates type of lift curve peak.

TABLE V.—MOMENT COEFFICIENT AT ZERO LIFT, C_{m_0}

Thickness designation / Camber designation	06	09	12	15	18	21	25	12	Theor.
00	−0.002	−0.003	−0.002	0.000	−0.002	−0.001	−0.003	−0.002	0
22	------	------	------	------	------	------	------	−0.029	−0.0370
23	−.036	−.036	−.036	−.034	------	------	------	−.038	−.0447
24	−.039	−.044	−.042	−.040	−.037	−.036	------	−.044	−.0531
25	−.048	−.052	−.050	−.049	−.047	−.043	------	−.054	−.0628
26	------	------	------	------	------	------	------	−.060	−.0749
27	------	------	------	------	------	------	------	−.075	−.0912
42	------	------	------	------	------	------	------	−.059	−.0739
43	−.075	−.073	−.072	−.068	−.065	−.057	------	−.075	−.0894
44	−.087	−.086	−.087	−.083	−.078	−.071	------	−.089	−.1062
45	−.109	−.106	−.102	−.097	−.094	−.082	------	−.105	−.1257
46	------	------	------	------	------	------	------	−.124	−.1497
47	------	------	------	------	------	------	------	−.143	−.1825
62	------	------	------	------	------	------	------	[1] −.087	−.1109
63	[1] −.109	−.110	−.108	−.105	−.097	−.090	------	−.110	−.1342
64	[1] −.129	−.133	−.129	−.125	−.118	−.110	------	−.132	−.1594
65	[1] −.159	−.158	−.154	[1] −.150	−.139	−.129	------	[1] −.159	−.1885
66	------	------	------	------	------	------	------	[1] −.186	−.2246
67	------	------	------	------	------	------	------	[1] −.206	−.2737

[1] Based on straight portion of moment curve extended. See curve for actual value.

TABLE VI.—DISPLACEMENT OF CONSTANT MOMENT POSITION IN PERCENT CHORD AHEAD OF QUARTER-CHORD POINT (100 TIMES VALUES OF n FOR EQUATION $C_{m_{c/4}}=C_{m_0}+nC_L$)

Thickness designation / Camber designation	06	09	12	15	18	21	25	12
00	0.7	0.7	0.9	1.1	1.4	1.8	2.6	0.9
22	------	------	------	------	------	------	------	.4
23	.3	.3	.3	.5	------	------	------	.5
24	.1	.3	.4	.7	1.0	1.5	------	.6
25	.0	.2	.3	.6	1.0	1.7	------	.7
26	------	------	------	------	------	------	------	.8
27	------	------	------	------	------	------	------	.8
42	------	------	------	------	------	------	------	.3
43	.3	.4	.5	.7	1.2	1.6	------	.4
44	.3	.3	.5	1.0	1.4	1.7	------	.5
45	.3	.3	.8	.9	1.4	1.7	------	1.0
46	------	------	------	------	------	------	------	1.1
47	------	------	------	------	------	------	------	1.3
62	------	------	------	------	------	------	------	.2
63	−.4	.1	.4	.9	1.1	1.5	------	.5
64	−.7	.0	.6	.9	1.3	1.7	------	.8
65	.0	.0	.7	1.6	1.8	1.9	------	1.5
66	------	------	------	------	------	------	------	2.0
67	------	------	------	------	------	------	------	2.1

TABLE VII.—MINIMUM PROFILE-DRAG COEFFICIENT, C_{D_0} *min*

Thickness designation / Camber designation	06	09	12	15	18	21	25	12
00	0.0065	0.0074	0.0083	0.0093	0.0108	0.0120	0.0143	0.0083
22	------	------	------	------	------	------	------	.0087
23	.0073	.0083	.0088	.0100	------	------	------	.0089
24	.0070	.0080	.0090	.0099	.0112	.0127	------	.0085
25	.0073	.0081	.0089	.0103	.0112	.0126	------	.0088
26	------	------	------	------	------	------	------	.0089
27	------	------	------	------	------	------	------	.0090
42	------	------	------	------	------	------	------	.0092
43	.0080	.0089	.0101	.0107	.0119	.0134	------	.0095
44	.0076	.0086	.0095	.0105	.0116	.0132	------	.0092
45	.0087	.0093	.0103	.0113	.0125	.0138	------	.0095
46	------	------	------	------	------	------	------	.0099
47	------	------	------	------	------	------	------	.0104
62	------	------	------	------	------	------	------	.0101
63	.0092	.0101	.0108	.0120	.0130	.0144	------	.0102
64	.0086	.0094	.0104	.0120	.0132	.0146	------	.0104
65	.0093	.0100	.0111	.0127	.0141	.0154	------	.0106
66	------	------	------	------	------	------	------	.0114
67	------	------	------	------	------	------	------	.0126

TABLE VIII.—OPTIMUM LIFT COEFFICIENT, $C_{L_{opt}}$

Thickness designation / Camber designation	06	09	12	15	18	21	25	12	[1]C_{L_I}
00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
22	------	------	------	------	------	------	------	.17	0.308
23	.17	.18	.10	.10	------	------	------	.15	.272
24	.23	.17	.15	.12	.11	.07	------	.20	.256
25	.18	.16	.15	.11	.08	.03	------	.23	.251
26	------	------	------	------	------	------	------	.20	.256
27	------	------	------	------	------	------	------	.20	.272
42	------	------	------	------	------	------	------	.35	.616
43	.35	.30	.23	.12	.20	.05	------	.34	.544
44	.40	.36	.33	.22	.16	.10	------	.32	.512
45	.40	.34	.27	.22	.16	.08	------	.30	.502
46	------	------	------	------	------	------	------	.30	.512
47	------	------	------	------	------	------	------	.33	.544
62	------	------	------	------	------	------	------	.55	.923
63	.63	.45	.40	.33	.24	.13	------	.47	.816
64	.60	.55	.42	.33	.24	.15	------	.45	.767
65	.60	.53	.42	.33	.24	.10	------	.45	.754
66	------	------	------	------	------	------	------	.38	.767
67	------	------	------	------	------	------	------	.30	.816

[1] Theoretical lift coefficient at "ideal" angle of attack.

TABLE IX.—RATIO OF MAXIMUM LIFT COEFFICIENT TO MINIMUM PROFILE-DRAG COEFFICIENT, $C_{L_{max}}/C_{D0_{min}}$

Thickness designation / Camber designation	06	09	12	15	18	21	25	12
00	135	172	184	164	138	115	84	184
22	------	------	------	------	------	------	------	184
23	142	182	182	154	------	------	------	181
24	144	189	177	156	128	106	------	190
25	141	170	180	148	132	109	------	184
26	------	------	------	------	------	------	------	187
27	------	------	------	------	------	------	------	187
42	------	------	------	------	------	------	------	186
43	150	180	161	146	123	96	------	172
44	162	186	170	150	127	104	------	179
45	132	168	164	143	123	106	------	178
46	------	------	------	------	------	------	------	178
47	------	------	------	------	------	------	------	175
62	------	------	------	------	------	------	------	173
63	167	165	152	129	110	95	------	163
64	166	179	159	133	114	97	------	160
65	139	171	158	132	114	97	------	165
66	------	------	------	------	------	------	------	161
67	------	------	------	------	------	------	------	155

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 755

REQUIREMENTS FOR SATISFACTORY FLYING QUALITIES OF AIRPLANES

By ROBERT R. GILRUTH

1941

For sale by the Superintendent of Documents, Washington, D.C. - Price 15 Cents

Reprinted by NASA Langley Research Center 1992

INTRODUCTION

By

Dr. James R. Hansen

In the early days of aviation, flying-quality specifications were derived almost soley from subjective pilot impressions of how their airplanes handled or reacted to different stimuli such as turbulence, stalls, high-speed turns or other difficult maneuvers, and so forth. As a result of this professional practice, aircraft designers were hard pressed to know just what the pilots meant when they spoke of "tail heaviness" or "lightness of controls." This was a terrible oversimplification, of course, not to mention an impossibility. It was then left up to the contractor to guess what the client wanted in terms of stability and control, maneuverability, and handling qualities. But in truth the client had no clear idea of what he wanted; he only knew that his pilots would complain in no uncertain terms if just that right "magical" feeling was not there when flying the airplane.

Beginning in the middle of the 1930s, aeronautical engineers at the NACA's Langley Memorial Laboratory (today's NASA Langley Research Center) learned to relate flying qualities in precise quantitative terms. This made meaningful communication among pilots, military and civilian aviation bureaus, and aircraft manufacturers much easier. In the early 1940s, at the conclusion of the comprehensive NACA flight test program described in the following NACA report by NACA researcher Robert R. Gilruth, engineers knew for the first time what flying qualities pilots actually desired, and they had a numerical means by which to specify those flying qualities for future design competitions. In other words, aeronautical engineering had matured to the point where its practitioners wanted to demystify the primary device that defined what they did as engineers, and that device was the airplane itself.

Besides its role in demystifying the flying qualities of aircraft, this influential NACA report of 1941 is also historically significant because its author, Robert R. Gilruth, eventually moved on in the late 1950s to head the famous Space Task Group in charge of Project Mercury, America's first manned space program. As the first director of the Manned Spacecraft Center in Houston, Texas, Gilruth played a critical leadership role also in the Gemini and Apollo programs.

Dr. James R. Hansen is a professor of history at Auburn University and the author of Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1858.

April 1992

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INTRODUCTION

The need for quantitative design criterions for describing those qualities of an airplane that make up satisfactory controllability, stability, and handling characteristics has been realized for several years. Some time ago, preliminary studies showed that adequate data for the formulation of these criterions were not available and that a large amount of preliminary work would have to be done in order to obtain the information necessary. It was apparent that flight tests of the flying qualities of numerous airplanes were required in order to provide a fund of quantitative data for correlation with pilots' opinions.

Accordingly, a program was instituted which covered the various phases of work required. The first step involved the development of a test procedure and test equipment which would measure the characteristics on which flying qualities depend. This phase of the work is reported in reference 1, although since that time the test procedure has been expanded and modified on the basis of additional experience and several changes have been made in the equipment used.

Another phase of the investigation has involved the measurement of the flying qualities of a number of airplanes. The procedure used has been in general in accord with that described in reference 1. At the present time (1941), complete tests of this nature have been made of 16 airplanes of varied types. These airplanes were made available largely by the Army and more recently by private companies at the request of the Civil Aeronautics Board. In addition, flying-qualities data of more limited scope have been obtained from time to time on a number of other airplanes, the tests of which covered only particular items of stability and control but which, nevertheless, augment the fund of data now available.

A third phase of the investigation, one which also has been pursued throughout the duration of the project, has involved the analysis of available data to determine what measured characteristics were significant in defining satisfactory flying qualities, what characteristics it was reasonable to require of an airplane, and what influence the various design features had on the observed flying qualities.

In order to cover this work adequately, a number of papers dealing separately with the various items of stability and control are necessary. Several such papers have been prepared or are in preparation at the present time. Detailed studies of all items will require considerable time for completion, but it is believed that the conclusions reached to date are complete enough to warrant a revision of the tentative specifications set forth in reference 1. As opportunity for additional analysis occurs, it would be desirable to cover the individual requirements at more length than is possible at this time. As a result of further studies, it may also be desirable to revise again the flying-qualities specifications given here.

In addition to the actual specifications, the chief reasons behind the specifications are discussed. Wherever possible, interpretation of the specification is made in terms of the design features of the airplane unless the subject is covered in reports of reference.

In formulating the specifications, every attempt has been made to define the required characteristics in easily measurable, yet fundamental terms. It was necessary to consider all stability and control requirements in arriving at each individual item because of the varied functions of the individual controls and the conflicting nature of many of these functions.

The specifications require characteristics that have been demonstrated to be essential for reasonably safe and efficient operation of an airplane. They go as far toward requiring ideal characteristics as present design methods will permit. Compliance with the specifications should insure satisfactory flying qualities on the basis of present standards, although as additional knowledge is obtained it may be possible to demand a closer approach to ideal characteristics without in any way penalizing the essential items of performance.

FLYING-QUALITY REQUIREMENTS

It has been convenient to present the flying-quality requirements under the following individual headings. They appear in the report in this order.

I. Requirements for Longitudinal Stability and Control
  A. Characteristics of uncontrolled longitudinal motion
  B. Characteristics of elevator control in steady flight
  C. Characteristics of elevator control in accelerated flight
  D. Characteristics of elevator control in landing
  E. Characteristics of elevator control in take-off
  F. Limits of trim change due to power and flaps
  G. Characteristics of longitudinal trimming device

II. Requirements for Lateral Stability and Control
  A. Characteristics of uncontrolled lateral and directional motion
  B. Aileron-control characteristics
  C. Yaw due to ailerons
  D. Limits of rolling moment due to sideslip
  E. Rudder-control characteristics

F. Yawing moment due to sideslip
G. Cross-wind force characteristics
H. Pitching moment due to sideslip
I. Characteristics of rudder and aileron trimming devices

III. Stalling Characteristics

These requirements pertain to all flight conditions in which the airplane may be flown in normal or emergency operation, with the center of gravity at any point within the placarded limits. Some of the specifications are based on the behavior of the airplane at some specified airspeed. The airspeed in such cases shall be taken as the indicated airspeed. Where minimum airspeed is referred to, unless otherwise stated, it shall be taken as the minimum airspeed obtainable with flaps down, power off.

With the exception of part III of the requirements, which deals exclusively with characteristics at or close to the stall, the requirements pertain to behavior of the airplane in the range of normal flight speeds at angles of attack below the angle of attack at which the stall would occur.

In the specifications which follow, the lower limits of the control-force gradients are specified in terms of the ability of the controls to return to trim positions upon release from deflected positions. This is a very desirable characteristic because it assures a control friction sufficiently low in comparison with the aerodynamic forces to allow the pilot to feel the aerodynamic forces on the controls. However, some additional interpretation of the specifications is necessary, because no control system can be made entirely free of friction and, therefore, there will always be some small deviation from return to absolute trim. At the present time, it is not possible to fix the allowable limits for these deviations. It is known, however, that controls reasonably free from friction, as measured on the ground, have satisfactory self-centering characteristics in the air as long as there is a definite force gradient. For elevators, force gradients as low as 0.05 pound per mile per hour have been satisfactory when the friction was small. For relatively small airplanes such as fighters, trainers, and light airplanes, it appears that about 2 pounds of friction in the elevator control system and 1 pound in the aileron represent an upper limit. In several cases, where push-pull rods with ball bearings were used throughout the control system, friction in both elevator and aileron systems has been found to be under ½ pound.

For large airplanes not intended to maneuver where visual or instrument references are always available, self-centering characteristics are not believed to be essential, although they are very desirable. In these airplanes control friction should be kept as low as possible, although there is indication that considerably more friction can be tolerated. A representative amount of control friction for a transport or medium bomber would be about 10 pounds in the elevator system and 6 pounds in the ailerons.

Irreversible controls have somewhat similar characteristics to controls with high friction; that is, they are not self-centering and therefore tend to destroy control feel. They are not considered desirable, although on very large airplanes where the rates of deviation from steady flight are slow they have been used successfully on ailerons.

I. Requirements for Longitudinal Stability and Control

Requirement (I–A).—Characteristics of uncontrolled longitudinal motion.

When elevator control is deflected and released quickly, the subsequent variation of normal acceleration and elevator angle should have completely disappeared after one cycle.

Reasons for requirement (I–A).—The requirement specifies the degree of damping required of the short-period longitudinal oscillation with controls free. A high degree of damping is required because of the short period of the motion. With airplanes having less damping than that specified, the oscillation is excited by gusts, thereby accentuating their effect and producing unsatisfactory rough-air characteristics. The ratio of control friction to air forces is such that damping is generally reduced at high speeds. When the oscillation appears at high speeds as in dives and dive pull-outs, it is, of course, very objectionable because of the accelerations involved.

The short-period oscillations involve variations of the angle of attack at essentially constant speed and should not be confused with the well-known long-period (phugoid) oscillation, which involves variation of speed at an essentially constant angle of attack. As shown by the tests of reference 2, the characteristics of the latter mode of longitudinal motion had no correlation with the ability of pilots to fly an airplane efficiently, the long period of the oscillation making the degree of damping unimportant. Subsequent tests have not altered this conclusion. The case of pure longitudinal divergence of the airplane (static instability) will be covered later under requirements of the elevator control in steady flight. No requirement for damping of the long-period phugoid motion appears justifiable at the present time.

Design considerations.—A theoretical analysis of this problem (reference 3) has shown that the damping of the control-free (short-period) oscillation is dependent chiefly on the magnitude of the aerodynamic balance of the elevators and on the mass balance and moment of inertia of the control system. The analysis shows that the damping is improved by reducing the aerodynamic balance, increasing the mass balance, and reducing the moment of inertia. The introduction of friction damping in the control system should, of course, also be effective although control friction is very undesirable for other reasons.

Requirement (I–B).—Characteristics of elevator control in steady flight.

1. The variation of elevator angle with speed should indicate positive static longitudinal stability for the following conditions of flight:

a. With engine or engines idling, flaps up or down, at all speeds above the stall.

b. With engine or engines delivering power for level flight with flaps down (as used in landing approach), landing gear down, at all speeds above the stall.

c. With engine or engines delivering full power with flaps up at all speeds above 120 percent of the minimum speed.

2. The variation of elevator control force with speed should be such that pull forces are required at all speeds below the trim speed and push forces are required at all speeds above the trim speed for the conditions requiring static stability in item 1.

3. The magnitude of the elevator control force should everywhere be sufficient to return the control to its trim position.

4. It should be possible to maintain steady flight at the minimum and maximum speeds required of the airplane.

Reasons for requirement (I–B).—Items 1 and 2 require positive static stability for flight conditions in which the airplane is flown for protracted lengths of time, or where opportunity exists to establish a trim speed so that stable characteristics can be realized. Positive static stability is not considered particularly helpful to a pilot at very low speeds with full power on or with flaps extended with full power on, because of the large trim changes due to power usually experienced. The conditions are classed as emergency conditions because in actual operation they are entered suddenly from approach conditions, where relatively little power is used. In these cases the elevator force and position changes, due to applied power and change of flap setting, are usually far greater than any inherent stable or unstable force or position gradients which exist due to the degree of static stability present. For these reasons, static stability in these conditions is not considered essential, at least not until trim changes due to power are reduced to much lower values than are experienced at the present time. The magnitude of allowable trim change due to power and flaps is covered later in requirement (I–F).

In other conditions of flight, however, static stability is regarded as an essential flight characteristic. Item 1 pertains to the elevator-fixed condition. This requirement insures that the airplane will remain at a given angle of attack or airspeed as long as the elevator is not moved, and provided that disturbed motion of the airplane is not left uncontrolled for long periods of time. Positive stability eliminates the need for constant control manipulation in maintaining given conditions and, furthermore, simplifies the control manipulation when a speed change is desired, because the direction of control movement required to start the rotation in pitch corresponds to that required to trim at the new angle of attack. A negative slope to the elevator-angle curve is a necessary requirement for elevator control feel, and the degree of control feel increases as the variation of elevator angle with angle of attack is increased (reference 4). In general, it may be said that the variation of elevator angle with angle of attack should be negative and as large numerically as is consistent with other requirements of elevator control.

Item 2 requires that the elevator-free static longitudinal stability shall always be positive. This specification insures that the airplane will not depart from a trim speed except as a result of definite action on the part of the pilot.

Item 3 requires that the elevator control be self-centering, a characteristic which is necessary for the attainment of control feel.

The reason for item 4 is obvious.

Design considerations.—A detailed analysis of the static longitudinal stability characteristics of various airplanes and the influence of various design features on the observed characteristics is given in reference 5.

Requirement (I–C).—Characteristics of the elevator control in accelerated flight.

1. By use of the elevator control alone, it should be possible to develop either the allowable load factor or the maximum lift coefficient at every speed.

2. The variation of elevator angle with normal acceleration in steady turning flight at any given speed should be a smooth curve which everywhere has a stable slope.

3. For airplanes intended to have high maneuverability, the slope of the elevator-angle curve should be such that not less than 4 inches of rearward stick movement is required to change angle of attack from a C_L of 0.2 to $C_{L_{max}}$ in the maneuvering condition of flight.

4. As measured in steady turning flight, the change in normal acceleration should be proportional to the elevator control force applied.

5. The gradient of elevator control force in pounds per unit normal acceleration, as measured in steady turning flight, should be within the following limits:

  a. For transports, heavy bombers, etc., the gradient should be less than 50 pounds per g.

  b. For fighter types, the gradient should be less than 6 pounds per g.

  c. For any airplane, it should require a steady pull force of not less than 30 pounds to obtain the allowable load factor.

Reasons for requirement (I–C).—Item 1 of this specification requires that sufficient elevator control should be available to execute maneuvers of the minimum radius inherent in the aerodynamic and structural design of the airplane. Since the curvature of the flight path is directly related to the normal acceleration, it is obvious that the attainment of either the maximum lift coefficient or the allowable load factor is the limting condition.

Item 2 is a requirement for stability in turning flight. Airplanes that do not meet this requirement tend to "dig in" and overshoot desired accelerations in maneuvers, even though every use is made of visual and instrument references.

Item 3 specifies the amount of stability required of an airplane which must be maneuvered at or close to maximum lift without resort to visual or instrument references. It has been demonstrated by tests of several fighter airplanes that longitudinal stability and control characteristics as specified are necessary for airplanes that require a high degree of control feel. The provision of such characteristics also reduces the time required to change angle of attack in entering rapid turns or zooms due to the simplified control manipulation associated with a definitely stable airplane.

The linear stick-force gradients specified in item 4 are, of course, very desirable as an aid to the pilot in obtaining the accelerations desired.

The numerical limits specified for the force gradients in item 5 are such that the minimum radius may be readily attained in any airplane. For pursuit types, gradients greater than 6 pounds per g were considered heavy by pilots. For airplanes where the load factor is lower, such as bombers, transports, etc., which are not required to maneuver continuously, a gradient of 50 pounds per g is not excessive. To insure against inadvertent overloading of the structure, the 30-pound lower limit (item 5–c) is necessary. For pursuit airplanes with allowable load factors of 9, this lower limit would correspond to a gradient of about 4 pounds per *g*. For airplanes with lower load factors, such as bombers, transports, or light airplanes, the gradient in pounds per *g* would be proportionately higher.

Important design factors.—In turning flight, due to the curvature of the flight path, a stabilizing effect is obtained which increases the slope of the elevator-angle curve over that obtained in straight flight. The stick forces required to maintain a given lift coefficient are considerably greater than those for straight flight, however, because the elevator angles are higher and because they are obtained at greater speeds. For this reason, it is necessary to specify the upper limit of elevator-force gradients only for accelerated flight.

A linear relation between stick force and normal acceleration is always obtained provided the elevator-angle curve and hinge-moment coefficient curve have linear variations with angle of attack and deflection, respectively.

Requirement (I–D).—Characteristics of the elevator control in landing.

1. (Applicable to airplanes with conventional landing gear only.) The elevator control should be sufficiently powerful to hold the airplane off the ground until three-point contact is made.

2. (Applicable to airplanes with nose-wheel type landing gear only.) The elevator control should be sufficiently powerful to hold the airplane from actual contact with the ground until the minimum speed required of the airplane is attained.

3. It should be possible to execute the landing with an elevator control force which does not exceed 50 pounds for wheel-type controls, or 35 pounds where a stick-type control is used.

Reasons for requirement (I–D).—For airplanes with conventional landing gear, the three-point attitude usually corresponds closely to that for the development of minimum speed for landing. In addition, an airplane alighting simultaneously on main wheels and tail wheel is less likely to leave the ground again as a result of possessing vertical velocity at the time of contact.

The reason for item 2 is obvious.

The limits of allowable control force in landing were determined from considerations of the pilot's capabilities. The limit forces given are 80 percent of those which a pilot can apply with one hand to the different control arrangements with the control 12 inches from the back of the seat. (See references 4 and 6.)

Design factors.—The requirements of the elevator in producing three-point or minimum speed landings are by far the most critical from a standpoint of control power. Flight-test data show that low-wing monoplanes with flaps down require about 10° more up elevator to land than to stall in comparable conditions at altitude. Without flaps this increment due to ground effect is not so great, and with high-wing monoplanes without flaps the landing frequently requires less elevator than the power-off stall at altitude.

Requirement (I–E).—Characteristics of elevator control in take-off.

During the take-off run, it should be possible to maintain the attitude of the airplane by means of the elevators at any value between the level attitude and that corresponding to maximum lift after one-half take-off speed has been reached.

Reasons for requirement (I–E).—The attitude of an airplane for optimum take-off characteristics depends upon the condition of the runway surface. On smooth, hard surfaces with low rolling friction the shortest take-off run is obtained with a tail-high attitude. Where rolling friction is high, however, it is advantageous to maintain an attitude which gives high lift.

Design considerations.—Adequate control of the attitude angle during take-off depends more on the proper location of the landing gear with respect to the center of gravity than on the characteristics of the elevators themselves. This requirement certainly is not critical from a standpoint of elevator control. An airplane that has sufficient tail volume to be stable and sufficient elevator control to perform three-point or minimum-speed landings should meet this requirement easily, as long as the main landing-gear wheels are properly located.

Requirement (I–F).—Limits of trim change due to power and flaps.

1. With the airplane trimmed for zero stick force at any given speed and using any combination of engine power and flap setting, it should be possible to maintain the given speed without exerting push or pull forces greater than those listed below when the power and flap setting are varied in any manner whatsoever.
   a. Stick-type controls—35 pounds push or pull.
   b. Wheel-type controls—50 pounds push or pull.

2. If the airplane cannot be trimmed at low speeds with full use of the trimming device, the conditions specified in item 1 should be met with the airplane trimmed full tailheavy.

Reasons for requirement (I–F).—It is desired that emergency manipulations of flaps or throttles do not require simultaneous adjustments of the trimming device. The force limits specified are approximately 80 percent of the maximum that a pilot can apply with one hand. The one-hand limit is necessary to allow the adjustment of throttles, flaps, or trimming device while complete longitudinal control is maintained. It is, of course, desirable that the trim changes be less than the limiting values given. The ideal condition would be one where the stick forces required for trim were not influenced by the position of the flaps or throttles.

It is also desirable that the control position required to maintain a given speed or lift coefficient be independent of the power and flap position insofar as possible. It is not, however, believed reasonable or necessary to specify any definite limits at this time.

Design factors.—Because of simultaneous changes in downwash, dynamic pressure at the tail, and pitching moment of the airplane less tail, the trim change produced by variations of power and flap setting are very difficult to predict. Several of the effects, however, have opposite signs, so that with sufficient care it should be possible to restrict the trim changes to a reasonably low value. Wind-tunnel tests of a powered model of the design under consideration would be a great help if not an absolute essential in this connection.

Requirement (I–G).—Characteristics of the longitudinal trimming device.

1. The trimming device should be capable of reducing the elevator control force to zero in steady flight in the following conditions:

a. Cruising conditions—at any speed between high speed and 120 percent of the minimum speed.

b. Landing condition—any speed between 120 percent and 140 percent of the minimum speed.

2. Unless changed manually, the trimming device should retain a given setting indefinitely.

Reasons for requirement (I–G).—It is, of course, desirable to be able to reduce the elevator force to zero in conditions where the airplane must be flown for protracted lengths of time. It is also desirable to be able to establish a trim condition within the allowable speed limits of the airplane so that release of the controls will not put the airplane in a dangerous position.

The reasons for item 2 are obvious.

II. Requirements for Lateral Stability and Control

Requirement (II–A).—Characteristics of uncontrolled lateral and directional motion.

1. The control-free lateral oscillation should always damp to one-half amplitude within two cycles.

2. When the ailerons are deflected and released quickly, they should return to their trim position. Any oscillations of the ailerons themselves shall have disappeared after one cycle.

3. When the rudder is deflected and released quickly, it should return to its trim position. Any oscillation of the rudder itself shall have disappeared after one cycle.

Reasons for requirement (II–A).—Because of its relatively short period, the lateral oscillation must be heavily damped. It is not logical to specify limits for the period of the oscillation because the period is dependent on factors covered by other specifications and also because the period is dependent on the size, speed, and weight of the airplane. The amount of damping specified in item 1 has been obtained with all satisfactory airplanes tested.

Items 2 and 3 of the requirement (II–A) are included to insure stability in the behavior of the lateral controls themselves.

Attention is called to the omission of a requirement for spiral stability. Tests have shown that the lack of spiral stability has not detracted from the pilot's ability to fly an airplane efficiently. In fact, it is very difficult to determine whether an airplane is inherently spirally stable or not, because divergence will occur with a spirally stable airplane if perfect lateral and directional trim do not exist or if slight asymmetry in engine power occurs in a multiengine airplane. For these reasons a large amount of inherent spiral stability would be required to insure against lateral divergence under actual conditions.

Since it appears that the degree of spiral stability or instability is inconsequential or at least of doubtful importance under actual conditions, it is desirable to avoid any such requirement because the design conditions for spiral stability conflict with other factors known to be essential in the attainment of satisfactory flying qualities.

Design considerations.—The theory of dynamic stability has been rather extensively developed from a mathematical standpoint. The charts of reference 7 make the calculation of the dynamic characteristics a relatively simple matter, provided the stability derivatives are known. In general, however, the stability derivatives are not known and cannot be estimated to a reasonable degree of accuracy, particularly with power on.

On the basis of experience, however, it appears that the damping requirement is not a critical design condition. There is every indication that when other requirements of fin area and dihedral are met, the uncontrolled lateral motion will be satisfactory.

Items 2 and 3 of the requirement (II–A) are dependent, as was the elevator-free motion (requirement (I–A)), on the control-hinge moments, mass balance, and moment of inertia of the control systems.

Requirement (II–B).—Aileron - control characteristics—(rudder locked).

1. At any given speed, the maximum rolling velocity obtained by abrupt use of ailerons should vary smoothly with the aileron deflection and should be approximately proportional to the aileron deflection.

2. The variation of rolling acceleration with time following an abrupt control deflection should always be in the correct direction and should reach a maximum value not later than 0.2 second after the controls have reached their given deflection.

3. The maximum rolling velocity obtained by use of ailerons alone should be such that the helix angle generated by the wing tip, $pb/2V$, is equal to or greater than 0.07 where

p maximum rolling velocity, radians per second
b wing span
V true airspeed, feet per second

4. The variation of aileron control force with aileron deflection should be a smooth curve. The force should everywhere be great enough to return the control to trim position.

5. At every speed below 80 percent of maximum level-flight speed, it should be possible to obtain the specified value of $pb/2V$ without exceeding the following control-force limits:

a. Wheel-type controls: ±80 pounds applied at rim of wheel.

b. Stick-type controls: ±30 pounds applied at grip of stick.

Reasons for requirement (II–B).—Item 1 of this requirement states an obviously desirable condition for any control; i. e., that the response shall be proportional to deflection.

Item 2 is designed to eliminate controls that are unsatisfactory from a standpoint of lag in the development of the rolling moment, or controls in which the initial rolling action is in the wrong direction.

Item 3 was obtained by correlation of pilots' opinions and measured characteristics for some 20 different airplanes of various types and sizes (reference 8). It was found that pilots judged the adequacy of their lateral control on the basis of the helix angle generated by the wing tip of the airplane. Airplanes giving values of $pb/2V$ less than 0.07 were always considered unsatisfactory.

Item 4 is a requirement for self-centering characteristics of the lateral control. This is a necessary condition for satisfactory control feel.

The specification of item 5 was determined by the limitations of pilots in applying forces to the lateral controls. Lower forces are, of course, desirable.

Design considerations.—Item 1 represents a normal characteristic of conventional flap-type ailerons, provided they are not deflected beyond the range where their effectiveness is linear. Certain spoiler-type ailerons, however, have been unsatisfactory because of their failure to meet this requirement. In these cases, the variation of effectiveness with deflection was either markedly nonlinear or such that appreciable movements of the control about the neutral point were required before the ailerons became effective.

Item 2 also is met by all conventional flap-type ailerons. Again, however, certain arrangements of lateral controls that depend on spoiler action have proved unsatisfactory because of lag or incorrect initial development of the rolling moment. Detail information on various satisfactory and unsatisfactory spoiler types may be found in reference 9 and later reports on the subject.

The specification of the helix angle, $pb/2V \geqq 0.07$ of item 3, corresponds approximately to requiring a rolling moment coefficient C_l of 0.035 or greater. Actually since $pb/2V$ is equal to the ratio of the rolling-moment coefficient to the damping-movement coefficient C_l/C_{l_p} a criterion in terms of C_l alone is not strictly applicable. The damping-moment coefficient tends to decrease with increased taper of the wing and to increase with increased aspect ratio. However, for the aspect ratios and taper ratio likely to be used, the criterion considered in terms of rolling-moment coefficient alone, $C_l \geqq 0.035$, should be satisfactory. In several types tested, particularly the very large airplanes, control-cable stretch resulted in a very serious loss of aileron effectiveness. There is also indication that wing twist under the torsional loads applied by ailerons should be considered in an interpretation of the rolling-moment coefficient required to obtain the specified value of $pb/2V$.

Item 4 sets the upper limit for aileron control friction since the ability of a control to center itself depends on the ratio of the inherent force gradient to the frictional force.

The control-force limits of item 5 are, of course, critical at the high speed specified. This requirement can be met by using existing design methods without servo control or mechanical booster systems except, perhaps, for the very largest airplanes that appear at this time.

Requirement (II–C).—Yaw due to ailerons.

With the rudder locked at 110 percent of the minimum speed, the sideslip developed as a result of full aileron deflection should not exceed 20°.*

Reasons for requirement (II–C).—Aileron yaw is responsible not only for annoying heading changes as a result of the use of ailerons but also for a reduction of aileron effectiveness unless the rudder is carefully manipulated to eliminate the sideslip induced. This latter effect is also dependent on the rolling moment due to sideslip (dihedral effect).

The requirement for aileron yaw expressed in this manner clearly separates satisfactory characteristics from those considered unsatisfactory by pilots and, moreover, has the merit of relating the factors responsible for aileron yaw in a fundamental manner. The limiting condition of 20° sideslip seems surprisingly high, but the number of satisfactory airplanes that develop sideslip angles substantially this great cannot be ignored. The requirement, however, is written to cover the critical low-speed conditions. At cruising speeds, comparable tests would give sideslip angles of the order of 5°.

Design considerations.—The sideslip due to ailerons is chiefly dependent on the aileron yawing moment, the yawing moment due to rolling, the dihedral effect, and the directional stability of the airplane. Compliance with the requirement depends mainly on the provision of sufficient directional stability, since the aileron yawing moment and the yawing moment due to rolling are determined by the aileron power. Of course, the designer has some control over the adverse aileron yawing moment through the use of differential in the control system and by increasing the profile drag of the up aileron. These effects, however, are generally small in comparison with inherent yawing moments due to ailerons and rolling velocity, which are always adverse in sign.

The required amount of directional stability is simply that which will give an equilibrium of the yawing moments at or below the angle of sideslip specified. The adverse aileron yawing moments can, of course, be determined in the wind tunnel. The yawing moment due to rolling for wings of various plan forms is given in the charts of reference 10.

Requirement (II–D).—Limits of rolling moment due to sideslip (dihedral effect).

1. The rolling moment due to sideslip as measured by the variation of aileron deflection with angle of sideslip should vary smoothly and progressively with angle of sideslip and should everywhere be of a sign such that the aileron is always required to depress the leading wing as the sideslip is increased.

2. The variation of aileron stick force with angle of sideslip should everywhere tend to return the aileron control to its neutral or trim position when released.

3. The rolling moment due to sideslip should never be so great that a reversal of rolling velocity occurs as a result of yaw due to ailerons (rudder locked).

Reasons for requirement (II–D).—Item 1 insures that the roll due to rudder will always be in the correct direction and that any lateral divergence will not be of a rapid type. It is also a necessary but not a sufficient condition for the ability to raise a wing by means of the rudder.

Item 2 is required to insure that the rolling moment due to sideslip will be of the correct sign with controls free. The

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*The measured sideslip angle on which this and subsequent specifications are based should not be confused with the angle of bank of the airplane. The angle of sideslip is simply that given by a vane free to pivot about a vertical axis and aline itself with the relative wind.

ability of the control to self-center here again is a requirement for control feel.

The reason for item 3 is obvious.

Design considerations.—Wind-tunnel data showing the effects of flaps, wing plan form, and fuselage-wing arrangement on the rolling moment due to sideslip are given in references 11 and 12. These results are generally substantiated by flight test. With single-engine low-wing airplanes, however, the dihedral effect in sideslips made to the left sometimes became negative at low speeds with power on, even though it was satisfactory with power off or with power on at higher speeds. Low-wing monoplanes generally required from 4° to 8° more geometric dihedral angle than high-wing monoplanes to obtain the same effective dihedral effect. On airplanes with the trailing edges of the wing swept forward, flaps reduced the effective dihedral and, where the trailing edge of the wing was a continuous straight line, flaps had little or no effect on the dihedral effect.

In order to meet item 2, the friction in the aileron control system must be low and the aileron required to overcome the rolling tendencies in the sideslip (dihedral effect) must exceed that at which the ailerons would tend to float due to the spanwise angle-of-attack variation.

The upper limit of the rolling moment due to sideslip (item II–D–3) is dependent on the yaw due to ailerons (item II–C–1) and the power of the aileron control (item II–B–3).

Requirement (II–E).—Rudder-control characteristics.

1. The rudder control should everywhere be sufficiently powerful to overcome the adverse aileron yawing moment.
2. The rudder control should be sufficiently powerful to maintain directional control during take-off and landing.
3. On airplanes with two or more engines, the rudder control should be sufficiently powerful to provide equilibrium of yawing moments at zero sideslip at all speeds above 110 percent of the minimum take-off speed with any one engine inoperative (propeller in low pitch) and the other engine or engines developing full rated power.
4. The rudder control in conjunction with the other controls of the airplane should provide the required spin-recovery characteristics.
5. Right rudder force should always be required to hold right rudder deflections, and left rudder force should always be required to hold left rudder deflections.
6. The rudder forces required to meet the above rudder-control requirements should not exceed 180 pounds (trim tabs neutral).

Reasons for requirement (II–E).—The reasons for these various items are obvious. Item 1 must, of course, be met if satisfactory turns are to be made at low speeds unless, of course, the directional stability is very great. Item 2 represents one of the most important functions for rudder control, although if a tricycle landing gear is used it becomes much less important.

Items 3 and 6 should insure adequate control over asymmetric thrust following engine failure subsequent to take-off. It does not seem necessary to retain directional control below the speed specified because of the probability that lateral instability due to stalling would set in first. The 180-pound force limit specified is about 90 percent of the maximum that an average pilot can apply.

Design considerations.—The rudder power needed to meet item 1 of the above requirement can be determined in the same manner that the directional stability required by aileron yaw was found (requirement (II–C)).

In at least one instance, item 2 of the above requirements was met without any rudder control. This was accomplished by using a tricycle landing gear and by eliminating the rudder-position variation with speed and power. However, due to the inherent instability of conventional landing gear, a certain amount of rudder control during take-off and landing will always be required when this arrangement is used, even though the rudder-trim change due to power or speed were eliminated. Just how much rudder is needed here is not known. The efficiency of the brakes, type of tail wheel (lockable or free-swiveling), and the magnitude of the inherent ground-looping tendency undoubtedly enter into the problem. Also, in landing, the stalling characteristics of the airplane may have an important bearing. On the basis of data on hand, however, it appears that a rudder control that is sufficiently powerful to meet the other requirements outlined should generally be satisfactory from a standpoint of ground handling.

Items 3, 4, and 5 do not appear to require additional discussion.

Requirement (II–F).—Yawing moment due to sideslip (directional stability).

1. The yawing moments due to sideslip (rudder fixed) should be sufficient to restrict the yaw due to ailerons to the limits specified in requirement (II–C–1).
2. The yawing moment due to sideslip should be such that the rudder always moves in the correct direction; i. e., right rudder should be required for left sideslip and left rudder should be required for right sideslip. For angles of sideslip between ±15°, the angle of sideslip should be substantially proportional to the rudder deflection.
3. The yawing moment due to sideslip (rudder free) should be such that the airplane will always tend to return to zero sideslip regardless of the angle of sideslip to which it has been forced.
4. The yawing moment due to sideslip (rudder free with airplane trimmed for straight flight on symmetric power) should be such that straight flight can be maintained by sideslipping at every speed above 140 percent of the minimum speed with rudder free with extreme asymmetry of power possible by the loss of one engine.

Reasons for requirement (II–F).—The reasons for item 1 are covered in discussion under requirement (II–C).

Item 2 of this requirement states a desirable characteristic for any control; i. e., the response should be proportional to the deflection.

Item 3 is designed to insure satisfactory directional stability, particularly at large angles of sideslip where vertical tail stalling has frequently led to trouble. This requirement follows directly from the results of reference 13.

Item 4 is included to prevent the directional divergence following an engine failure from being excessively rapid. Although the ability to fly with rudder free on asymmetric power is probably not in itself important, it is undoubtedly strongly related to the rate of divergence and therefore the required quickness of action on the part of the pilots when this emergency occurs.

Design considerations.—The directional stability required to fulfill item 1 has been discussed under requirement (II–C).

General discussion of the factors that determine the fin area required to meet items 2 and 3 of this requirement is given in reference 13. However, the interference effects of wing-fuselage position, vertical tail arrangement, etc., are so great that wind-tunnel tests would appear a necessary aid to design for these requirements. Since the directional stability at large angles of sideslip, however, is related to the manner in which the flow breaks down on the vertical surfaces, and on its effect on the floating characteristics of the rudder, the scale of the test should be kept as great as possible.

Requirement (II–G).—Cross-wind force characteristics.

The variation of cross-wind force with sideslip angle, as measured in steady sideslips, should everywhere be such that right bank accompanies right sideslip and left bank accompanies left sideslip.

Reasons for requirement (II–G).—Under normal conditions in a sideslip or skid, a force is produced which acts toward the backward-lying wing tip. Since the actual angle of sideslip cannot be observed by the pilot, the cross-wind force developed allows appreciation of the fact that sideslip exists because of the lateral acceleration which occurs. In steady sideslips the cross-wind force is balanced by a component of the weight of the airplane, so that an angle of bank results. The greater the cross-wind force the greater is the angle of bank. An approximate relation between angle of bank ϕ and the cross-wind force may be written as follows:

$$\phi=\sin^{-1}\frac{\text{Cross-wind force}}{\text{Weight of airplane}}$$

In addition to providing the pilot with "feel" of the sideslip or skid, the lateral attitude from which it is possible to recover with the rudder alone (without permitting a heading change) is directly related to the magnitude of the cross-wind force. Obviously, a positive dihedral effect is also necessary for the performance of this maneuver, but the fact remains that turning toward the low wing will always occur if the lateral attitude from which recovery is attempted exceeds that which can be held in steady sideslip with full rudder.

For these and other reasons, large values of cross-wind force are desirable and more rigid specification than that given would lead to better flying qualities. On the other hand, it is not known whether this could be done without increasing the drag of the airplane.

None of the airplanes tested to date has failed to meet the requirement as written. It is included, however, because there is indication on the basis of wind-tunnel tests that some future designs may actually develop cross-wind force of opposite sign to that normally experienced. Obviously, this condition could not be tolerated.

Requirement (II–H).—Pitching moment due to sideslip.

As measured in steady sideslip, the pitching moment due to sideslip should be such that not more than 1° elevator movement is required to maintain longitudinal trim at 110 percent of the minimum speed when the rudder is moved 5° right or left from its position for straight flight.

Reasons for requirement (II–H).—A pitching-moment change due to sideslip is undesirable because it requires that the elevator as well as the rudder must be coordinated with the ailerons. Also, since sideslip of considerable amounts may be carried inadvertently, a marked variation of pitching moment with sideslip will tend to produce inadvertent angle-of-attack changes. The condition is critical at high lift coefficients, so compliance with the specifications given should automatically insure satisfactory characteristics at higher speeds.

Design considerations.—It is believed that the change in pitching moment with sideslip occurs as a result of the downwash change experienced by the horizontal tail as it moves from behind the wing center. In most cases, the moment produced is a diving moment because of the relatively high concentration of downwash at the wing center due to the propeller or partial-span flaps. It has also been noted that the magnitude of the pitching moment due to sideslip progressively decreased as the angle of attack was reduced, presumably because of the corresponding reduction of downwash angles.

Requirement (II–I).—Power of rudder and aileron trimming devices.

1. Aileron and rudder trimming devices should be provided if the rudder or aileron forces required for straight flight at any speed between 120 percent of the minimum speed and the maximum speed exceed 10 percent of the maximum values specified in requirements (II–B–5) and (II–E–6), respectively, and unless these forces at cruising speed are substantially zero.

2. Multiengine airplanes should possess rudder and aileron trimming devices sufficiently powerful, in addition, to trim for straight flight at speeds in excess of 140 percent of the minimum speed with maximum asymmetry of engine power.

3. Unless changed manually, the trimming device should retain a given setting indefinitely.

Reasons for requirement (II–I).—The reasons for the items listed above are obvious.

III. Stalling characteristics

1. The approach of the complete stall should make itself unmistakably evident through any or all of the following conditions:

   a. The instability due to stalling should develop in a gradual but unmistakable manner.

   b. The elevator pull force and rearward travel of the control column should markedly increase.

   c. Buffeting and shaking of the airplane and controls produced either by a gradual breakdown of flow or through the action of some mechanical warning device should provide unmistakable warning before instability develops.

2. After the complete stall has developed, it should be possible to recover promptly by normal use of controls.

3. The three-point landing attitude of the airplane should be such that rolling or yawing moments due to stalling, not easily checked by controls, should not occur in landing, either three-point or with tail-first attitude 2° greater than that for three-point contact.

Reasons for requirement (III).—The items of this requirement are in keeping with all others given; i. e., it demands all that can be obtained with existing knowledge and yet is sufficiently rigid so that any airplane that complies with the specification will be reasonably safe in terms of our present standards. Since there is never occasion in the normal operation of an airplane for a pilot to stall intentionally, such characteristics that provide warning of the stall are given first importance. If the warning is unmistakable, the relative violence of the actual stall loses much of its significance because it would then occur only as an intentional act on the part of the pilot and at a safe altitude. Item 2 is included to insure that recovery from an intentional stall can be promptly made.

Item 3 is an outgrowth of some experience in studying ground-handling problems. In most cases, poor stalling characteristics are troublesome in landing because of wing dropping either during the actual landing flare or after the airplane has alighted during the landing run. In other cases the wing stall has influenced the flow at the vertical tail in such a manner that powerful yawing moments have developed. Unless the stall itself can be made to develop in a gentle manner, the cure for these characteristics can be effected by preventing the occurrence of the stall altogether in the landing maneuver.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *March 24, 1941.*

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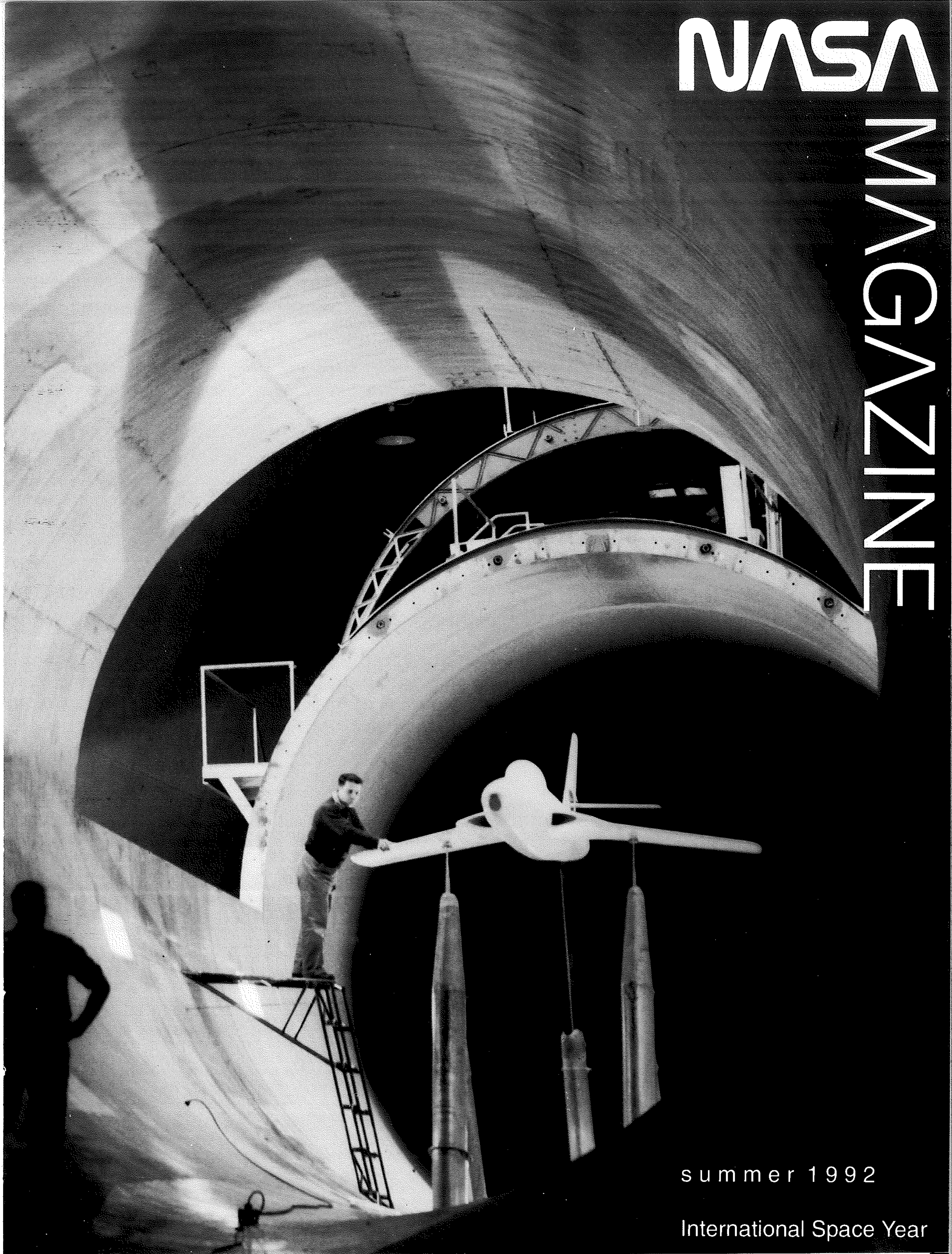

summer 1992

International Space Year

Dan Goldin becomes NASA's 9th administrator

Daniel Goldin, accompanied by his wife Judith and Vice President Dan Quayle, is sworn in as NASA's 9th Administrator by President Bush in the Oval Office.

"I can't tell you what an honor this is for me and how happy I am to come back to NASA. Over 30 years ago I sat down with my father and we filled out an application for the Lewis Research Center that started my career in civil space, the civil space program, and my membership on the NASA team.

To me, NASA is a symbol of America's competitive economic spirit…an investment in America's future…(and) the standard by which all other nations of the world measure their space programs. With your help, I intend to raise our standard even higher."

Administrator Daniel S. Goldin

Address to NASA Employees

April 1, 1992

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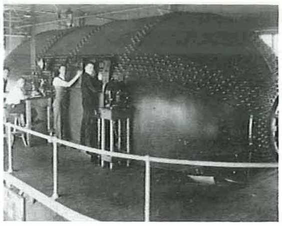

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NASA's eldest celebrates its 75th anniversary.

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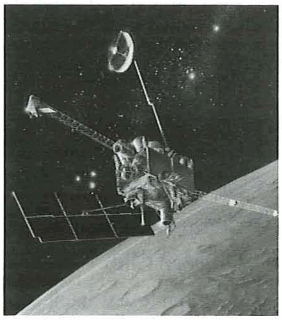
HEAVY METAL
It's a rocket! It's a plane! No, actually it's a souped-up NASA hot rod.



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TAKING THE MEASURE OF MARS
The Mars Observer goes for the big picture.

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SHEDDING NEW LIGHT ON LOW VISION
"Space glasses" derived from NASA technology offer hope to millions of Americans for whom ordinary eyeglasses don't help.

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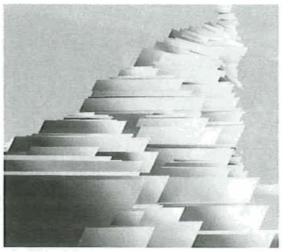
A DEFINING MOMENT
James Michener voices his thoughts on the importance of space exploration.



departments

Cover: A scale model of a Republic RF-84F Thunderflash is tested in LaRC's 19-foot pressure tunnel during the 1950's. After renovation, the tunnel became the transonic dynamic tunnel in 1960 and today continues to test aeroelastic phenomena. Cover photo and all photos for LaRC birthday story (see page 12) courtesy of LaRC.

NASA MAGAZINE

Acting Associate Administrator for Public Affairs
Sue Mathis Richard

Acting Manager of Internal Communications
Beth Schmid

Editor
Beth Schmid

Contributing Editor
Charles Redmond

Editorial Consultant
Tony Reichhardt

Editorial and Production Assistant
Sonja Alexander

Design
Steve Chambers

Art Director
Robert Schulman

Staff Photographer
Bill Ingalls

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Goldin, during a press conference at Johnson on May 11.

Goldin Meets the NASA Team

No sooner was Dan Goldin on the job than he began making the rounds, acquainting himself with NASA's centers. Within two days of his appointment as NASA Administrator, he visited the Kennedy Space Center to get a firsthand look at the Space Shuttle fleet in action, with the April 2 landing of Atlantis at the Florida Shuttle Landing Facility. "I've been to Shuttle launches before," said Goldin, "but I've never seen one land. It was an emotional experience."

At the Stennis Space Center on April 14, the administrator toured several facilities, and was briefed by key personnel on the center's current and upcoming programs. He also was the guest of honor at a reception attended by Stennis employees.

The Marshall Space Flight Center hosted Goldin on April 21, providing tours of the Project LASER Discovery Lab, the Productivity Enhancement Complex, and the U. S. Space and Rocket Center. Goldin addressed Marshall employees at a luncheon honoring secretaries and clerical personnel at the Redstone Arsenal Officers' Club.

Then it was back to Ohio, where Goldin had first worked for NASA 30 years ago. The new administrator visited the Lewis Research Center on April 22, touring several facilities and meeting with a cross-section of employees throughout the center. He challenged all Lewis employees to focus on how they can personally improve and measure their contributions to NASA.

On Thursday, May 28, Goldin visited the Jet Propulsion Laboratory where he challenged JPL employees to "strengthen ourselves and take risks...and yes, it is safe to take risks at NASA again."

On the final leg of his center tours, Goldin visited Goddard in June and plans to visit Ames Research Center and the Dryden Flight Research Facility in July.

Goldin put the NASA "meatball" insignia back into service while visiting Langley on May 22.

Goldin gets a closeup look at a Space Shuttle at Kennedy.

Mary Rose Palfy talks to Goldin about Lewis's system for processing invoices.

Goldin as guest of honor at a reception attended by all Stennis employees; with him is center Deputy Director, Gerald Smith.

Youth participating in Space Camp at the U. S. Space and Rocket Center meet Goldin during his Marshall visit.

The STS-45 crew was joined by an orbiting Oscar to pay tribute to George Lucas at the Academy Awards ceremony in March.

The space Oscar returns to its earthly home at the Academy of Motion Picture Arts and Science's Center for Motion Picture Study on May 27. Left to right: Gil Cates, producer of the Oscar telecast; STS-45 commander, Col. Charles Bolden; Administrator, Daniel Goldin; Academy President, Karl Malden; STS-45 crewmembers David Leestma with space-faring Oscar, and Brian Duffy.

An Oscar...

The biggest trick was getting Oscar ready for his trip to space. But after months of coordination and planning, the famous statuette's debut from low Earth orbit brought the house down during the Academy Awards ceremony in March.

NASA was first approached by the Academy of Motion Picture Arts and Sciences in the fall of 1990 with a request to consider flying one of its award statues onboard the Space Shuttle. The goal was to tie Oscar and the space program together for a tribute to filmmaker George Lucas, the recipient of this year's Irving J. Thalberg award for significant contributions to the motion picture arts and sciences.

Speaking for the STS-45 crew who flew with Oscar, Commander Charlie Bolden praised Lucas for exciting young people about space travel with his films. In accepting his award, Lucas thanked his teachers for inspiring him to pursue his dreams.

The space Oscar, having traveled nearly 4 million miles aboard Space Shuttle *Atlantis*, was returned home to the Academy of Motion Picture Arts and Science's Center for Motion Picture Study at a ceremony in Beverly Hills on May 27.

...and an Emmy

Linda Dukes-Campbell, now Lewis Research Center's chief of Community and Media Relations, was part of a team awarded a national Emmy recently for a program produced at WEWS in Cleveland. Dukes-Campbell, who worked at the station until last September, was associate producer of "Color-Blind," the one-hour kickoff to the station's year-long anti-prejudice and awareness campaign called "World of Difference."

In a day-long sensitivity session—part of a conference hosted by WEWS to foster awareness of racial prejudice— participants explored attitudes about race, sex, and age. This was followed by another session a month later. More than 12 hours of videotape were edited for the "Color-Blind" special, which received the Community Service Emmy Award last September from the National Association of Television Arts & Sciences. Although the station had previously won many local Emmys, this was their first national award.

Linda Dukes-Campbell

Dukes-Campbell said the special was probably the most powerful piece of journalism ever shown by a Cleveland television station. "It awakened a lot of feelings in the viewing audience. Everyone says, 'I am not a bigot.' Yet as this special showed, they perpetuate racism in subtle ways."

In her job at Lewis, Dukes-Campbell says her biggest challenge is to educate the local community about operations at NASA and to dispel the misconception many people have about government workers. "The work that people are doing here is phenomenal," she says. "These people work so hard!"

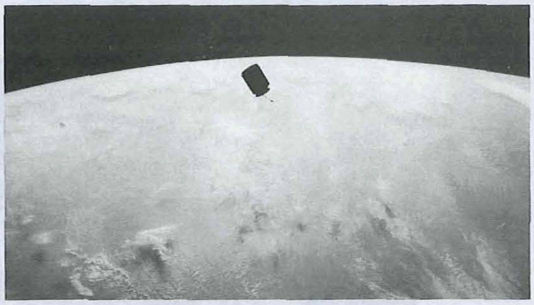
Long Ago and Far Away

Ames Research Center and NASA celebrated the 20th anniversary of the Pioneer 10 spacecraft on March 2. Launched from Kennedy Space Center onboard an Atlas-Centaur rocket in 1972, Pioneer 10 is now beyond the orbits of all the planets, having traveled more than five billion miles from Earth.

With its planetary investigations long finished, the spacecraft is exploring the region of the Sun's extended magnetic field and electrical field known as the heliosphere. Pioneer

ENDEAVOUR

STS-49 Endeavour crew: Left to right (front) Kathryn C. Thornton, Thomas D. Akers, and Richard J. Hieb; (back) Pierre J. Thuot, Daniel C. Brandenstein, Kevin P. Chilton and Bruce E. Melnick.



This scene of Intelsat VI greeted the STS-49 crewmembers as they prepared for their successful capture of the errant satellite.

Thuot's second-day unsuccessful attempt to affix the grapple bar to the 4.5 ton Intelsat.

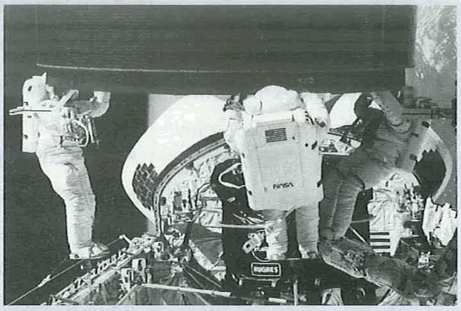
One For the Record Books

By the time the drama ended, a satellite had been repaired, a new spacewalk record had been set, and the nation, in the words of one newspaper account, "had a new set of heroes."

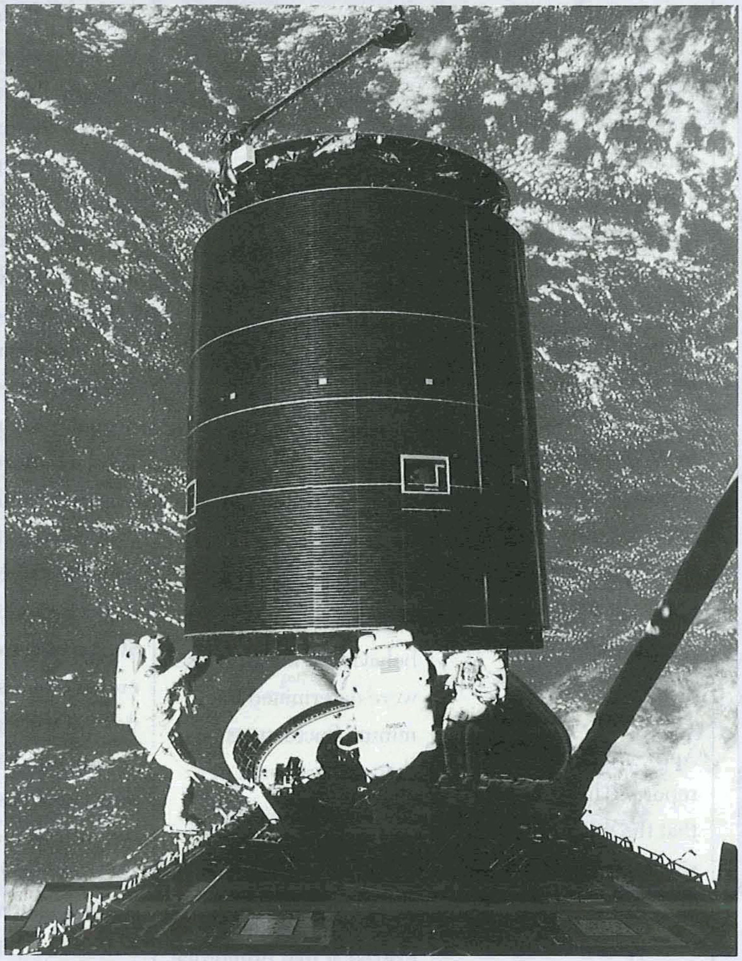
Endeavour roared off Launch Pad 39B on its inaugural STS-49 mission May 8 to rescue the Intelsat 6 spacecraft and practice assembly methods for Space Station Freedom. The mission, which finally was successful in capturing and repairing Intelsat after three tries, broke almost every spacewalk record, including the most ever—four—on a single flight. The third spacewalk was the first ever by three astronauts, and was the longest extravehicular activity (EVA) in history, surpassing even the walks taken on the surface of the Moon by the Apollo astronauts.

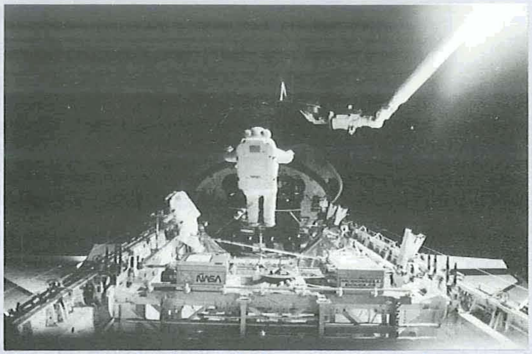
During the rescue phase, astronaut chief and mission commander Dan Brandenstein three times maneuvered Endeavour up to the Intelsat, the last time literally placing the satellite into the hands of Pierre Thuot, Richard Hieb and Thomas Akers. After grabbing the errant spacecraft, the three spacewalking astronauts then fitted it with a new booster motor so that it could climb to its proper geosynchronous orbit.

A fourth spacewalk after the Intelsat rescue allowed Akers and Kathryn Thornton to practice space station construction tasks. During the flight, the

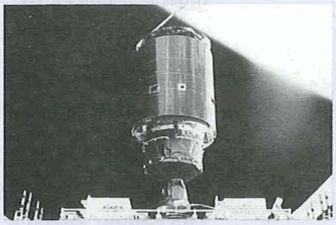


◀ Left to right, Hieb, Akers and Thuot have handholds on Intelsat VI, as they successfully capture the satellite. ▼

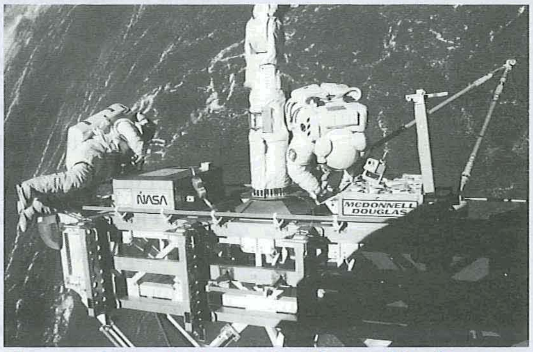




After securing Intelsat with the remote manipulator system, the crew prepares the satellite for release into orbit.



With its perigee kick motor in place, the Intelsat VI satellite spins slowly away from Endeavour's cargo bay.



Thornton (left) and Akers work with Assembly of Station components on the mission's fourth EVA.

crew noted that based on their experience in grappling the Intelsat 6, training for space station assembly will have to undergo some major changes.

Throughout the crew's travails, the performance of the nation's newest orbiter was flawless. The mission was extended twice and finally landed at California's Edwards Air Force Base on May 16.

After the successful satellite capture, President Bush and Vice President Quayle both phoned in their congratulations to Administrator Goldin, conveying, in Goldin's words, "every confidence in NASA to carry out bold research and exploration programs."

Later Goldin said of Endeavour's triumphant first mission, "Your achievements reflect the can-do attitude of the NASA of old and the new NASA of today." •

10 was the first craft to cross the asteroid belt and the first to fly past Jupiter—providing the first close images of the Solar System's largest planet. The 568-pound spacecraft, currently the most distant object built by humans, has enough velocity to escape the gravitational pull of the Sun. In the odd event that some other group of interested beings ever finds it, Pioneer 10 carries a plaque showing a representation of a man and a woman standing beside a likeness of the vehicle. The plaque, which is "written" in visual and binary code, also depicts our Solar System as the point of origin for the spacecraft's journey.

Three of NASA's four deep space vehicles are now heading toward the center of our galaxy, with Pioneer 10 heading in the opposite direction. All four are beyond Pluto, which is presently inside the orbit of Neptune. This three-dimensional spacecraft arrangement will help the space physics community in their continuing search for the edge of the Sun's influence—the heliopause—and the beginning of true interstellar space.

The Pioneer spacecraft is managed and controlled by Ames.

A Tomato is a Tomato is a...

Are "space seeds" different from ordinary seeds? NASA has analyzed the results of tomato seed experiments performed by more than 3.3 million students under the supervision of nearly 64,000 teachers. The seeds, which were flown aboard the Long Duration Exposure Facility for almost six years before being retrieved in January 1990, were distributed by NASA education offices as part of a student experiment to see if space-exposed seeds germinate and grow differently from ordinary Earth seeds. The results, published in April, are based on 8,000 reports. They suggest that the space-exposed seeds germinated faster and experienced a faster initial growth rate, but overall produced no noticeable difference in the fruit.

COBE Finds Structure in the Void

A major cosmological advance was announced in April by scientists using data gathered by the Cosmic Background Explorer (COBE). The scientists—George Smoot of the University of California at Berkeley, Charles Bennett of NASA's Goddard Space Flight Center, Edward Wright of UCLA, and others—announced they have detected the long-sought variations in the background radiation left over from the Big Bang. These variations show up as temperature fluctuations of only about thirty millionths of a degree Kelvin in different regions of the sky. The team's findings agree with the postulated "inflationary cosmology" theory for the origin of the Universe, which states that the structure and behavior of the Universe were determined by minute fluctuations less than one-trillionth of a second after the Bang. The amount of gravity determined by the COBE results to have existed at that primordial moment would not have been adequate to cause the creation of galaxies or clusters, lending support to the so-called "dark matter" theory, which holds that there is much material in the Universe that we have yet to detect.

Thirty Days Under the Sea

The Johnson Space Center's Behavior and Performance Laboratory is cooperating with the Marine Resources Development Foundation in Key Largo, Florida, on an experiment involving four men living for 30 days in an undersea laboratory. Because the crew will go on daily excursions to collect ocean research data, the experiment provides an analog to a lunar or Martian laboratory where teams also would make periodic forays outside to gather samples. The JSC laboratory will be studying the health and well-being of the men, including such factors as cognitive functioning ability and stress. The crewmembers' perceptions of work organization and general behavioral observations also will be recorded. JSC expects that this experiment will give a better understanding of the viability of certain procedures, as well as hardware and software that could be used for 30-day space missions. •

TRANSITION

Honored

For the second year in a row the Johnson Space Center has the distinction of employing the NASA Inventor of the Year. This year three JSC recipients—**P. David Wolf, Ray Schwarz,** and **Tinh Trinh**—are being recognized for their contributions to the development of a new class of tissue culture growth system. The trio worked on the design of the JSC bioreactor, which uses a slowly-rotating cell wall to stimulate the growth of tissue that is more like normal. This year the JSC team shares the Inventor of the Year award with a team from the Marshall Space Flight Center. Engineers **William Simpson, Max Sharpe** and **William Hill** were honored for their Sprayable Lightweight Ablative Coating, which is used to spray the Space Shuttle's reusable solid rocket boosters. The Marshall and Johnson inventor teams were toasted at the NASA Award Ceremony this March in Washington.

The National Space Club awarded the Goddard Trophy for 1992 to the **Magellan** project for the mission's success in mapping Earth's twin planet with unprecedented resolution and nearly complete coverage. The award was presented at the Club's annual Goddard Memorial Dinner.

Died

James E. Webb, NASA Administrator from 1961 to 1968, died in March after a heart attack. He was 85. Webb was universally credited for laying the groundwork for the success of the Apollo program, and during his tenure, the agency grew to include 35,000 staff members and about 400,000 contractors.

Thomas Otten Paine, NASA's third Administrator and a principal architect of this nation's space program, died of cancer at his home in Los Angeles on May 6. Paine, who led NASA during the Apollo lunar mission era, was 70. President Johnson appointed him as NASA Deputy Administrator under James Webb. When Webb retired in 1968, Paine became Administrator.

Changing Jobs

Associate Administrator for Space Flight **William Lenoir** resigned in May. Administrator Goldin named Major General **Jeremiah W. Pearson, III**, of the U.S. Marine Corps, as the new Associate Administrator for Space Flight. Goldin also named astronaut **Bryan O'Connor** as Deputy Associate Administrator for Space Flight.

Goldin also announced the appointment of astronaut **Charles Bolden** to be Assistant Deputy Administrator, responsible for integrating and ensuring the accomplishment of Total Quality Management review activities across the agency.

Darleen Druyun was appointed in May as Goldin's Chief of Staff. Goldin said "NASA intends to be world class in everything we do, and I view this appointment as being truly world class." Druyun's deputy, **Don Bush**, replaced her as Assistant Administrator for Procurement.

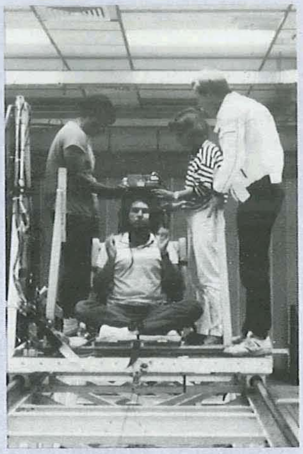
Laurie A. Broedling has been named as Associate Administrator for Continuous Improvement. She comes to NASA from the Department of Defense where she most recently served as the Deputy Under Secretary for Total Quality.

Astronaut **Fred Gregory** has been named by Administrator Goldin as the Associate Administrator for Safety and Mission Quality. **George Rodney**, who had been in this position since August 1986, retired in June.

Charles Pellerin, Jr. has been appointed as Deputy Associate Administrator for Safety and Mission Quality. In addition, Pellerin will work with recently announced Assistant Deputy Administrator Charles Bolden to assist Goldin in long-range planning.

Dr. Harriett Jenkins, Assistant Administrator for Equal Opportunity Programs at NASA since 1974, became the first Director of the Senate's Office of Fair Employment Practices on June 1. •

From conferences to training workshops to student rocket launches, International Space Year activities are taking place all over the world this summer.



University students in a NASA Life Sciences Training Program session test the reactions of a subject.

Up and Running

by Danelle K. Simonelli

Exciting things are happening in mid-1992 as the celebration of International Space Year continues. Global scientific projects initiated for ISY are now coming to fruition, and a wide variety of educational activities also are taking place:

Conferences: The ISY World Forest Watch Conference held from May 26 to May 29 in Brazil brought together scientists from around the globe to focus on the use of space technologies in monitoring deforestation. The next major ISY conference, the World Space Congress, will be held August 28-September 5 in Washington, D. C., when results of numerous ISY research projects will be presented. NASA will have a major exhibit there as well as several smaller exhibits, including a 50-ft. mockup of the National Aero-Space Plane, and plans to host the annual meeting of the Space Agency Forum on ISY (SAFISY), the international space agency coordinating group for ISY, in conjunction with the World Space Congress.

Many scientific and professional organizations also dedicated meetings to ISY, among them the May 26-29 International Geoscience and Remote Sensing Symposium in Clear Lake, Texas, and the May 30-June 4 International Conference on Engineering, Construction, and Operations in Space, held in Denver. Upcoming events include the August 2-14 Congress of the International Society for Photogrammetry and Remote Sensing in Washington, D.C., and the August 24-29 Planetary Congress of the Association of Space Explorers, also in the nation's capital.

Earth Science: A major theme of ISY is the Mission to Planet Earth, and several SAFISY Earth science projects already are showing results. NASA, which leads SAFISY's Greenhouse Effect Detection Experiment, recently released two of the project's CD-ROM disks containing data on the temperature and composition of Earth's atmosphere. Another innovative SAFISY effort, led by Canada's space agencies, is the GEOSCOPE Global Change Encyclopedia, the first interactive computerized encyclopedia of planet Earth, which recently premiered in prototype form.

Continuing through the year are a variety of SAFISY and United Nations training programs designed to help scientists in developing countries use satellite data in such areas as urban planning and the prediction of floods and earthquakes. The United States will host a U.N. conference in this series August 17-20 in Boulder, Colorado.

Educational Activities: The ISY Global Change Education Conference, co-sponsored by NASA, brought together educational, environmental, and civic leaders in Washington, D.C., on May 13. NASA's Space Life Sciences Training Program for university students, with expanded international participation for ISY, is ongoing at the Kennedy Space Center through the end of July.

Younger students met from March through May at sites across the United States to build "Marsville—the Cosmic Village," courtesy of the Challenger Center. Student rocket launchings, sponsored by the Rocket Research Institute and its counterparts worldwide, are continuing through the summer, highlighted by an international meet in Mourmelon, France, from July 23 to July 27. The International Space University will celebrate ISY by announcing plans for its permanent campus in conjunction with the World Space Congress.

These events are just some of the worldwide ISY activities this summer. Look for fall highlights and more upcoming events in the next issue of *NASA Magazine.* •

Danelle Simonelli is Information Director for the U.S. International Space Year Association.

For more information on these and other ISY projects, contact the U.S. International Space Year Association at (202) 863-1734.

Changing of the Guard

by Dr. John Lawrence,
Office of Legislative Affairs,
NASA Hq.

> This year's Congressional election may send as many as 150 new faces to Washington—most of whom will be eager to make good on their anti-incumbent, anti-big-spending campaign promises. From NASA's point of view, the result could be a hard job made even harder.

There's an element of magic in this year's election. As stage magicians use misdirection to make us look away from the significant action, so the glamour of the Presidential election is diverting our attention from what could be the most momentous Congressional contest in modern history.

In 1948, 118 seats changed hands in the Congressional election—the modern day record. However, a confluence of circumstances this year could result in a turnover of up to 150 or more seats. A change of this magnitude would have far-reaching consequences for the nation and for NASA.

Three major factors contribute to the expected high turnover: redistricting, a high rate of retirements and resignations, and anti-incumbent sentiment.

The redistricting as a result of the 1990 census will affect Congressional delegations in 43 states. Four states having NASA centers are favorably affected—California gains seven seats; Texas, three; Florida, four; and Virginia, one. Ohio, which is home to the Lewis Research Center, loses two seats. Some redistricting plans are still pending court approval, but estimates are that the next Congress (the 103rd) could have 20 new minority members. And in at least five cases, redistricting will set incumbents against each other.

Others are leaving Congress of their own free will. As of early May more than 50 members had announced their resignation or retirement, and more were anticipated. Already it's the highest number of resignations since the end of World War II. Of this group, thirteen have declared their intention to run for other offices (11 for the senate, two for governorships). Of the remainder, many have cited frustration with the system or pressures of the job as motivating influences.

Another contributing factor to the wave of resignations is a new rule dictating how PAC (Political Action Committee) money can be disbursed. Over the course of a Congressional career, donations to a member's re-election fund can produce a significant war-chest, and this is the last year departing members can convert this money to their own personal use. In subsequent years, campaign fund balances must go either to charity, other PACs or a political party.

Those members of Congress who intend to run for re-election face a national anti-incumbent mood precipitated by the sluggish economy, the growing deficit and the back-to-back revelations concerning unpaid bills at the Capitol restaurant, allegations of embezzlement and drug dealing at the House post office and check over-drafts at the House bank. Evidence of this mood already was apparent in the spring, by which time 12 incumbents had been defeated in primary elections. This is an extraordinarily high number, especially for so early in the process. By comparison, only one incumbent lost a primary in 1990, one in 1988, two in 1986, and three in 1984. Consequently, some incumbents may expect meaningful opposition in the remaining primaries as well as in the general election in November.

Members of the 103rd Congress will have ample motive to regard themselves as instruments of reform. Newcomers to office as well as returning incumbents will likely have campaigned on fiscal austerity and anti-Washington themes.

From NASA's point of view, the result could be a hard job made even harder. The membership of NASA's committees of jurisdiction surely will change, and voting patterns in the overall body may shift. Of the members already known not to be returning, nearly two-thirds voted with NASA to restore Space Station *Freedom* funds to the Fiscal Year 1992 appropriation. *Freedom* was saved by a margin of 67 votes—meaning a swing of 34 votes would have had the reverse effect. With more than a hundred new members predicted, the 103rd's freshmen would be a highly influential bloc.

Accordingly, NASA's early objective will be to educate the new members of the 103rd, and to preserve and strengthen the collegiality that exists with its committees of jurisdiction.

To do so, NASA may have to work some magic of its own.•

With some clever image enhancement provided by technicians at the Kennedy Space Center, Pennsylvania police were able to convict a murderer based on a few fuzzy frames captured on film at a bank teller machine.

Scenes of the Crime

by Mitch Varnes, KSC

NASA is known for discovering clues to the mysteries of the universe, but high-tech imagery and a group of dedicated Kennedy Space Center security officers recently joined forces to help police solve the murder of a Northumberland County, Pennsylvania woman.

On May 24, 1989, 19-year-old Lori Auker, of Point Township, Pennsylvania, disappeared while on her way to work at a local shopping mall. Auker's car was found in her usual parking space at the mall, but she never arrived at her destination. Authorities spent nearly three weeks looking for leads and scouring the countryside before Auker's body was discovered at a county landfill 19 days after her disappearance.

Police initially suspected that Lori's former husband, Robert, was involved in both her disappearance and death, but had no way of proving it. On a hunch, investigators requested the film from the camera of an Automatic Teller Machine (ATM) located several yards from where Lori had parked her car. A series of three black and white photographs taken just 13 minutes before Lori was due at work showed a bank customer in the foreground and some unusual occurrences in the background. Fuzzy and almost indistinguishable, the three images—snapped over a 20-second period—captured a car entering and leaving the camera's field of view. The second picture showed a female form matching Lori Auker's standing outside the passenger side. More importantly, the car in the photo appeared to be similar to a car owned by Robert Auker's father, a 1984 Chevrolet Celebrity that was sold only a couple of days after Lori was reported missing.

The search for the Chevrolet took longer than expected, but eventually it was recovered. When police went back to the shopping mall and recreated the scene using the ATM surveillance camera and the recovered car, the cars in the two films appeared nearly identical.

Pennsylvania police then spent months working with image specialists at the FBI and Eastman Kodak Company in attempts to further refine the original three frames. Their efforts proved helpful, but the results weren't incriminating enough to warrant an arrest.

Pennsylvania state police officer Tom Brennan then steered Northumberland District Attorney Robert Sacavage and detective George Allen to the Kennedy Space Center, where NASA uses computer enhancement of photographic images to provide detailed visual information of Space Shuttle and other rocket launches. The space agency also uses the technique to aid scientists in studying photographic images taken by planetary spacecraft, such as those that recently mapped Venus and returned the first closeup images of the asteroid Gaspra.

Allen and Sacavage subsequently traveled to the Florida spaceport with the ATM films in hand. There, Andy Casey, a security officer for EG&G Florida, KSC's base operations contractor, and fellow space center worker Al Tietjen took the films to a laboratory where Tietjen spent several days digitally enhancing the area of the photos that included the car. By breaking that particular segment into a series of tiny light and dark picture elements, Tietjen was able to sharpen the characteristics of the car so greatly that a General Motors Company engineer later identified the car in both the original and recreated photographs as most likely being the same automobile. With that enhanced imagery, the police and district attorney had enough substantive evidence to arrest Auker, who was later found guilty of both kidnapping and murder charges and sentenced to death. It was the first time the digital enhancement of photographic images had been used in a criminal prosecution.

In a letter to Casey after the verdict, Sacavage wrote, "This matter will undoubtedly have far-reaching effects for the law enforcement community throughout the United States. I am certain that the digital imaging process will be developed into a useful forensic scientific technique."

And that, according to Casey "gives us tremendous satisfaction—to see justice done and to be able to put NASA technology to work in our field." •

Astronaut Don Thomas spends his weekends helping children from broken homes to emerge from the shadows. "I'm there to listen and to expose them to a different way of life," he says.

A Friend in High Places

by Sonja Alexander, Hq.

At the age of 37, Don Thomas is a success by almost any standard. A PhD. in materials science, he became an astronaut candidate in 1990, and now works at the Johnson Space Center in the Astronaut Office's Safety and Operations Development Branch. But even though you might say he's already "arrived," Thomas hasn't forgotten what it's like to be young, alone, and struggling to make a place for yourself in the world. So he reaches out to lend a hand.

For the past three years, Thomas has worked with the United Way's "Friends of Students" program, which matches adult volunteers with students from the Clear Creek Independent School District in Houston. Many of the students, who range in age from 10 to 17, are from broken homes or are children of alcoholics. Some have been abused. All of them could use a friend.

Thomas typically gets to know a particular student over an extended time, so that a pattern of trust and bonding is established. "Our time together is one-on-one; we go to dinner and usually take in a movie." An astronaut's life is a hectic one, so most of the get-togethers come at the end of the work week. But if his schedule includes traveling on the weekend, Thomas spends time with the student during the week.

Thomas's own parents divorced when he was ten years old, so he can relate to some of the problems the students are facing. "Growing up in a single-parent household can be pretty rough sometimes. I didn't see my father for over twenty years, and that can really affect you," he says.

It takes a while for the students to open up enough to talk about their problems, he says. "I'm there to listen and to expose them to a different way of life." Thomas hopes that his obvious interest in science and technology and his commitment to the space program will rub off on the teenagers, even if they do sometimes get blasé about the idea of hanging out with an astronaut.

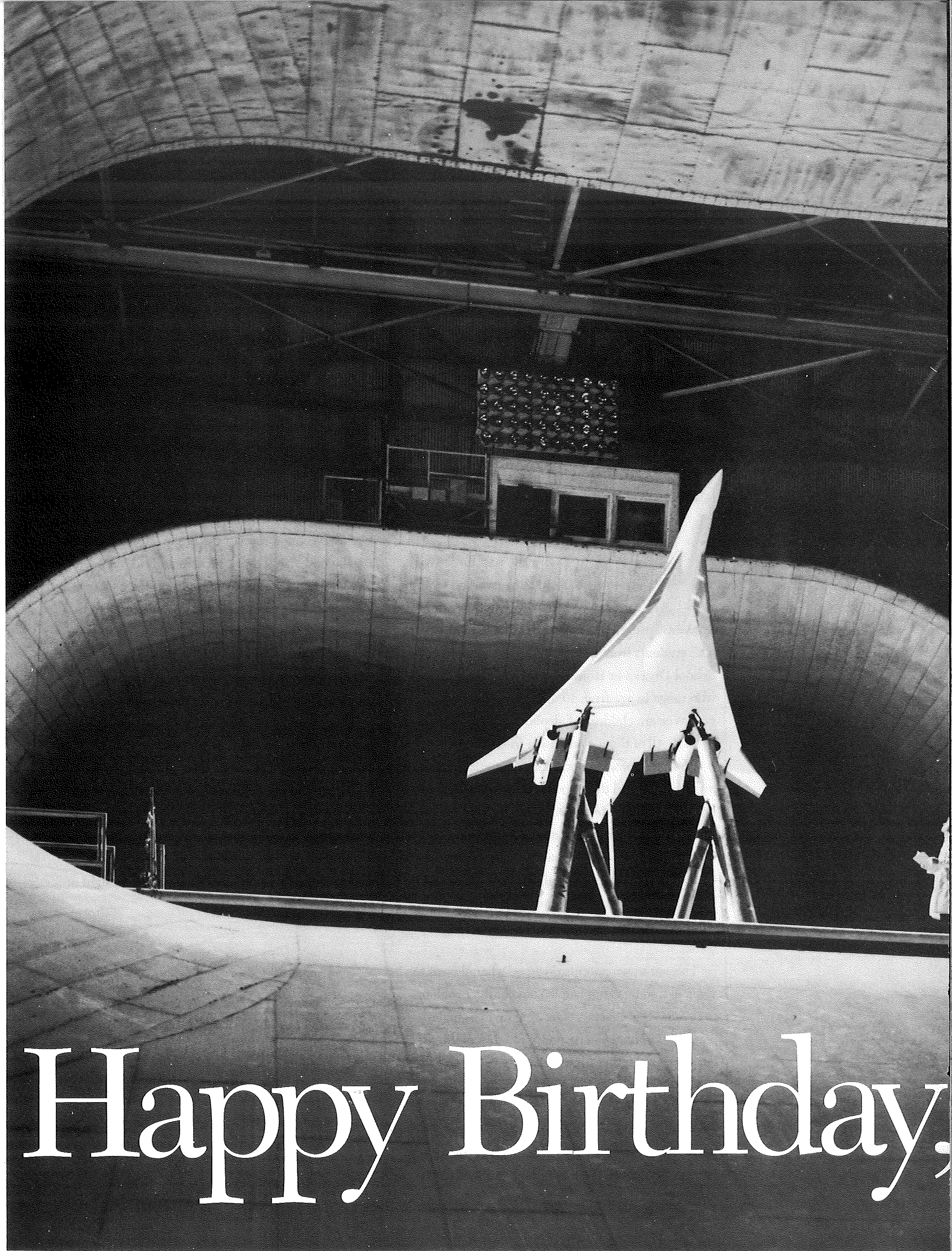
"It impresses their families more than it does the students," he says. "Their idols are usually rock stars, movie stars, and athletes."

Thomas sees his role as being a sounding board and a positive example. He points out to his students that none of his own achievements happened overnight, and that he, too, encountered failures along the way. Many kids from troubled homes have built a solid wall around themselves, he says. Some are shy and withdrawn, and some are just plain afraid.

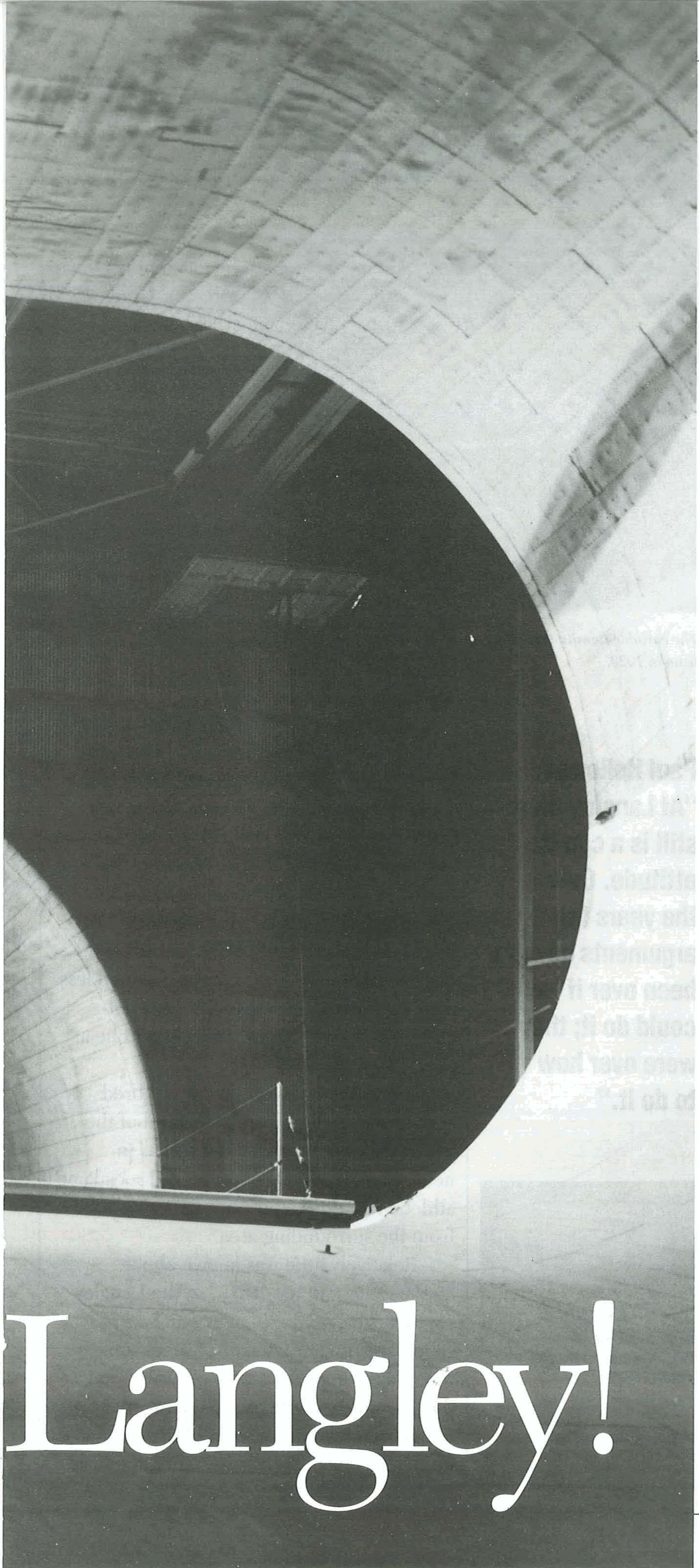
He recalls the time he arranged to take a ride with a student on a Goodyear blimp. "The captain asked him if he wanted to steer the blimp. Being somewhat shy, he said, 'No, I'll just sit here and ride.' I asked him how many people ever got to ride in a Goodyear blimp, let alone steer one, and encouraged him to give it a try. Reluctantly he did, and the smile on his face could have lit up the world. That was so satisfying to me. These students need encouragement, or they will always be in the shadows."

Thomas admits that he rarely gets a thank you, but says he's not doing it to get positive strokes. "I'm doing it because I know it's the right thing to do."

He set his own sights on becoming an astronaut when he was six years old, and his advice to students of all ages is to find a goal, work hard to accomplish it, and don't let failure defeat you. "Anyone can achieve great things in life if they don't lose sight of their dream," he says. •



Happy Birthday,



A model of a supersonic transport plane is tested in Langley's 30 × 60 ft. wind tunnel which has been operational since 1931.

Langley!

1917 - 1992
75 Years
NACA
NASA
Langley Research Center

NASA's eldest celebrates its 75th anniversary

by James Schultz

Few anecdotes from the history of flight research are as unusual as the one told about German-born aerodynamicist Max Munk.

Already a respected figure in the National Advisory Committee for Aeronautics (NACA) by the time he came to work at what was then called the Langley Aeronautical Laboratory in 1926, Munk had an autocratic, brook-no-dissent management style. It didn't take long for him to alienate a talented staff, resulting in his abrupt departure after only a year. Officially, Munk is remembered at Langley for his brilliance as a theorist; unofficially, for a stubborn highhandedness that clashed with the center's collegial, egalitarian culture.

As the story goes, Munk decided while at Langley that he wanted to learn how to drive. Ignoring the able instruction offered by a wind tunnel technician on his staff, he vowed to go it alone. He drew up a map of the road between his home in Hampton, Virginia and the Langley complex, calculating the exact distance between the road's various curves and the precise amount the car would need to turn at each of those curves. Munk then hung a string from the top of the steering wheel and applied numbered pieces of tape to indicate the degree of manipulation required to negotiate each turn. By driving at a predetermined speed, and with the help of a stopwatch and the aforementioned map, he successfully and safely navigated his way to and from the office.

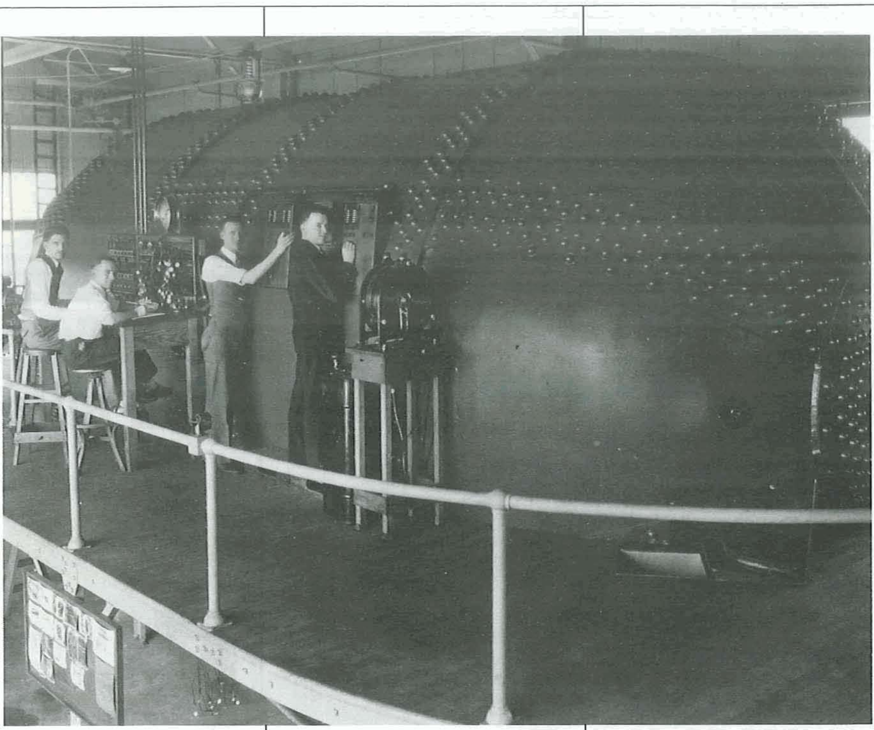
In his book, *Engineer In Charge: A History of the Langley Aeronautical Laboratory 1917-1958*, historian James Hansen calls this story "a sort of local legend, an extravagantly exaggerated one."

But there's also truth in it, he says.

"The key thing is that the folks at Langley tell such stories themselves," explains Hansen. "It's the flip side of the same coin. On one hand, the Munk story appears to be a critical one about someone losing it and going too far. But at the same time, the storytellers take pleasure in the telling: It's a mark of distinction to be that ingeniously different from everybody else."

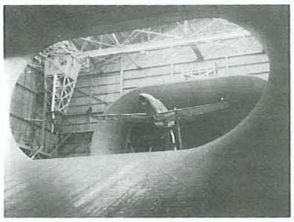
Self-sufficient ingenuity has always been one of the Langley Research Center's great virtues. As the eldest offspring of NACA and the nation's first federally funded civilian aeronautical research facility, the center began its life making do with limited resources. But make do Langley did, sometimes in spectacular fashion.

The laboratory was responsible for developing a number of the basic devices and procedures that made the modern airplane possible. Later, as a NASA research center, it led the way in developing America's manned space program. On July 17, the men and women of Langley celebrated 75 years of preeminent achievement in the technology of flight.



The variable-density tunnel team in 1929.

Paul Holloway: "At Langley there still is a can-do attitude. Over the years the arguments haven't been over if we could do it; they were over how to do it."



P-51 Mustang in the full-scale tunnel, 1943.

"We've done almost any mission one can think of, from aeronautics to astronautics," says Paul F. Holloway, the current center director. "And we've done it as active partners with industry. One of Langley's major achievements was the establishment of an infrastructure for what came to be known as the aerospace community. That's probably our greatest legacy."

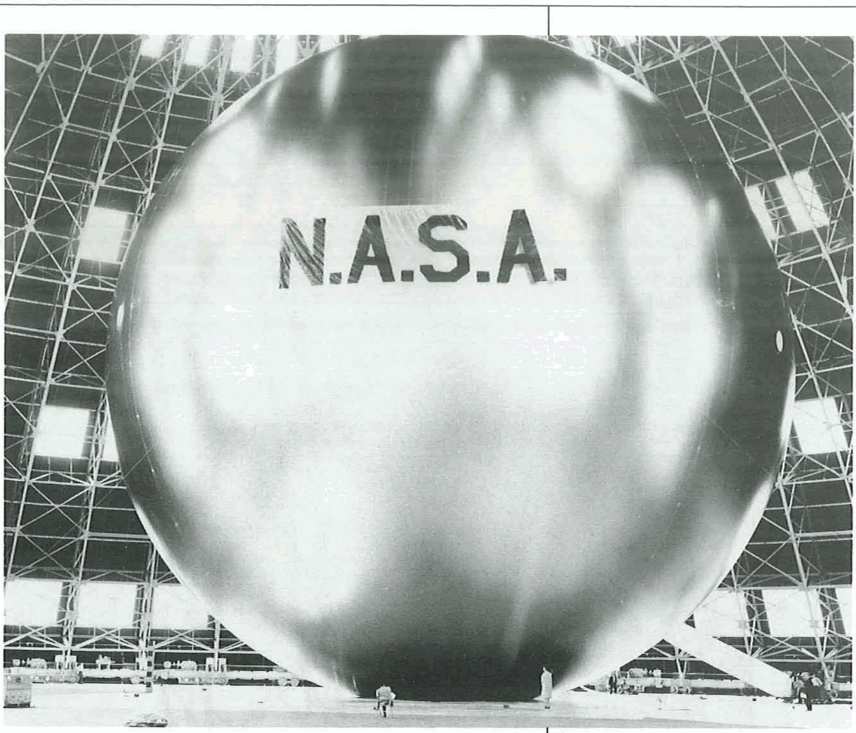
The Young and the Restless

If there was one thing that characterized the laboratory in the early years, it was the youthful enthusiasm of its staff. Most of the young men who came to work at Langley (until World War II, virtually all the research engineers were male) were from northern or midwestern states. Of those, many had grown up in or near large urban areas. To local farmers and fisherfolk, clannish and distrustful of outsiders, Langley seemed less a government facility than a Yankee enclave—and a suspiciously exuberant one at that.

But as time passed, familiarity bred contentment: The locals grew fond of the young engineers who rented rooms in nearby boardinghouses, organized social and athletic functions, and courted young ladies from the surrounding area.

Relatively little was known about airplane flight in the 1920s, so the Langley engineers set out to learn as much as possible. Because aerodynamic theory sometimes lagged behind practical application, the learning was often in the doing.

"Hired fresh out of school with a minimum knowledge of aerodynamics and little



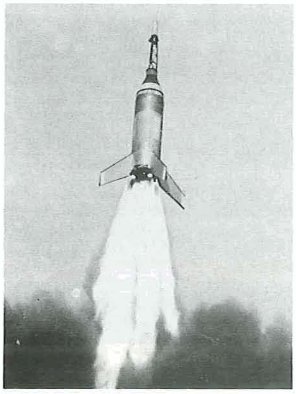
practical experience of any kind, the majority of these early Langley researchers learned nearly everything on the job," writes Hansen. "Because they were so young, they had not learned that a lot of things could not be done, so they went ahead and did them."

What the government engineers did, in close cooperation with the emerging aircraft industry, was essentially to reinvent the airplane. In 1928 Langley devised the nation's first streamlined engine cowling, a heralded advance that boosted aircraft speeds 16 percent simply by reducing drag. By the 1930s an aeronautics design revolution was well underway: The awkward, wire-braced, fabric-covered wooden flying machines of previous decades yielded to sleek metal craft that were faster and stronger. Planes like the DC-3 became the first of a new generation of aircraft that incorporated technology based on NACA's state-of-the-art aeronautical research.

Along with improved airplanes came efforts to design and build better wind tunnels and related research tools and labs. Starting with the Variable Density Tunnel in 1922, Langley's wind tunnel complex grew ever more sophisticated. One of the most notable achievements was the development by the late 1940s of a slotted-throat tunnel, which eliminated the "choking" problems that had so bedeviled researchers attempting to unravel the mysteries of the transonic flight regime. Improvements accelerated in succeeding decades. By the mid-1980s, the center's National Transonic Facility was up and running, and by the early '90s the 8-foot high temperature tunnel was being readied to accommodate large-scale hydrogen-fueled scramjet engine testing.

Suspended from the ceiling of a hangar, this 100-foot-diameter Echo satellite was test-inflated with forty thousand pounds of air while on Earth; in orbit, it only required a few pounds of gas to keep it inflated.

The Little Joe launch vehicle being prepared for a test launch from Wallops Island in 1960.



For several generations of motivated engineers, there were few better places to work than Langley. A position at the NACA laboratory in Hampton wasn't a mere job. For many it was a way of life. Even at lunch, equations would be scribbled, erased and rescribbled on marble countertops. Langley was the kind of place an impassioned aeronautical researcher could call home.

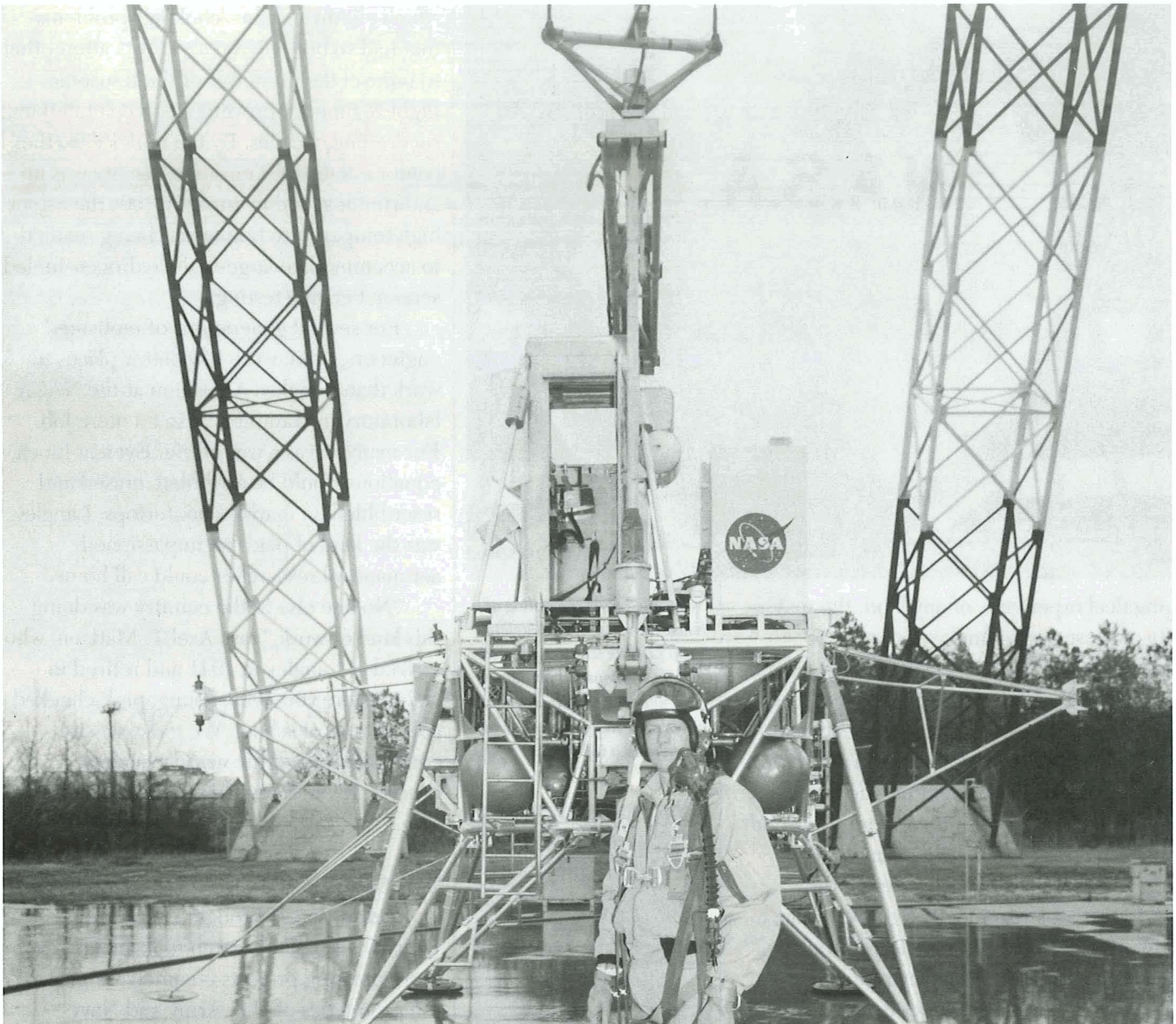
"No one else in the country was doing this kind of work," says Axel T. Mattson, who arrived at Langley in 1941 and retired in 1974. "Here you were, young, pink-cheeked and just out of school. We took [on-site] courses taught by the world's leading experts. It was so exciting it was unbelievable."

Into Space

World War II brought changes to Langley, as basic research took a back seat to more pressing projects—namely, improving the prototypes of U.S. Army and Navy aircraft. Because of wartime expansion, staff levels at the laboratory ballooned from 524 in 1939 to 3,220 by 1945.

Women also came to the center in unprecedented numbers, and one entire job category—"computers," or people who produced slide rule calculations and plotted data curves—became an exclusively female domain. This was not lost upon some of the laboratory's most dedicated male engineers, who quite literally married their computers.

By 1940, two NACA "daughter" centers had been established— Ames in California and Lewis in Ohio—and some of Langley's most accomplished personnel went west to staff these new facilities. Meanwhile, by



Not long after this photo was taken in front of Langley's Lunar Research Facility, astronaut Neil Armstrong became the first human to step upon the surface of the Moon.

war's end the center was turning its research energies toward the problem of breaking the so-called sound barrier. Langley researchers and test pilots played a major role in the effort that resulted in Captain Charles E. "Chuck" Yeager's historic supersonic flight on October 14, 1947.

During the war, Langley also had begun rocket research at Wallops Island, on Virginia's secluded Eastern Shore. Throughout the 1940s, researchers at Wallops worked with sounding rockets in an attempt to understand and analyze transonic and supersonic aerodynamic forces. By the time the Soviet satellite Sputnik broadcast its first orbital beeps to an astonished world in 1957, Langley's rocketeers already were prepared to pick up the gauntlet thrown down by the USSR.

Axel Mattson: "Here you were, young, pink-cheeked and just out of school. We took courses taught by the world's leading experts. It was so exciting it was unbelievable."

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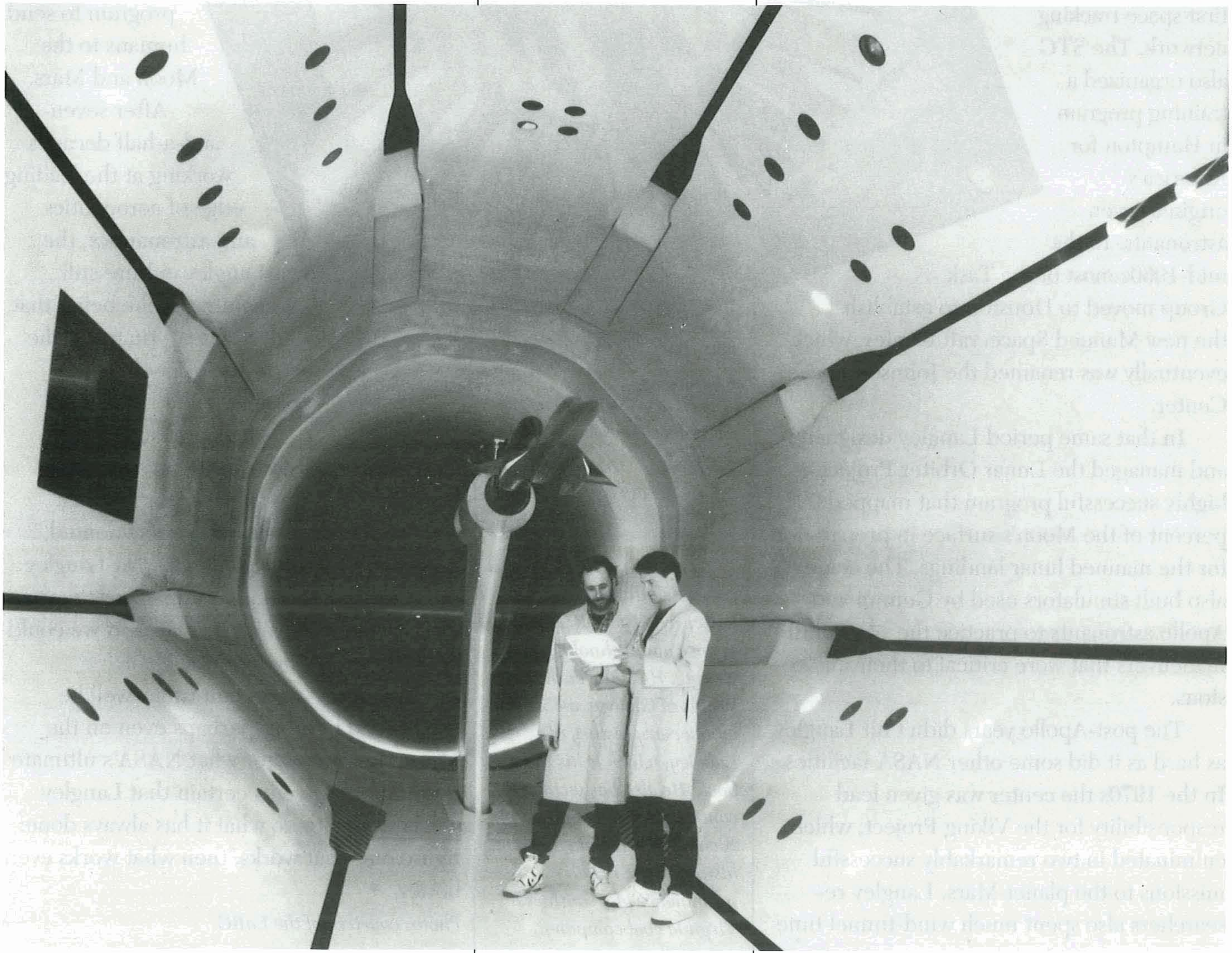
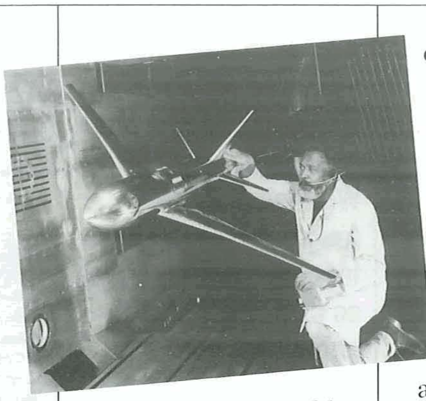
A model of a Boeing 737 is used to collect data in the Low Frequency Antenna Test Facility.



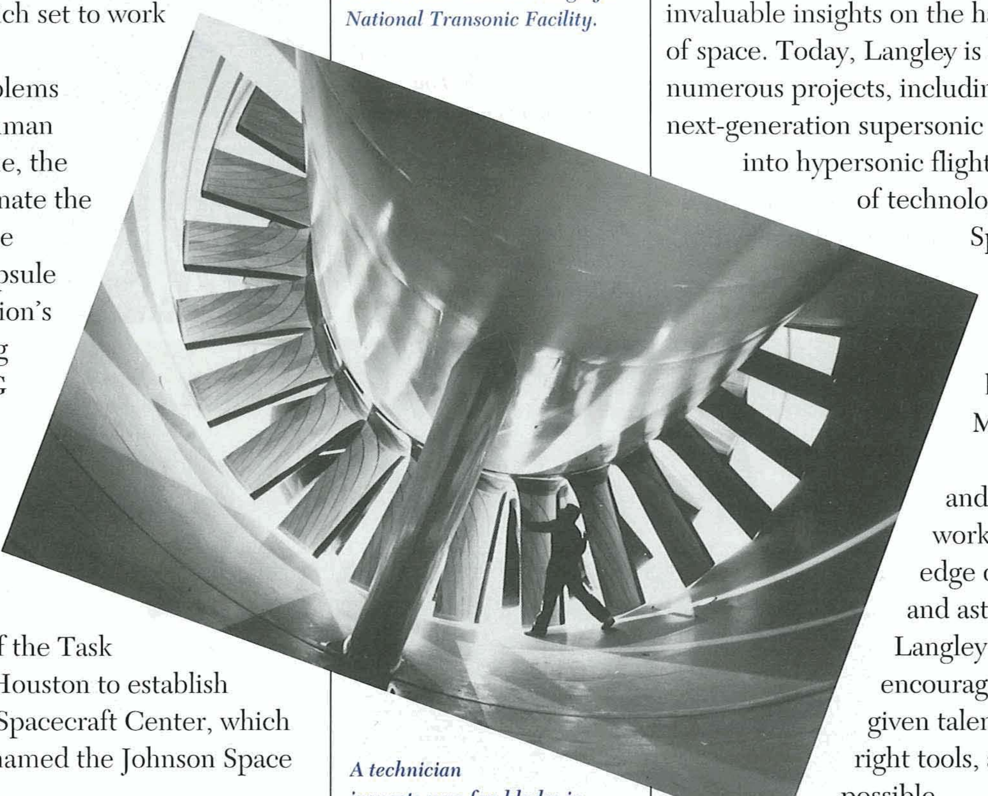
Two technicians review the test schedule for a model in the 16-ft. transonic wind tunnel.
▼

With the space race now underway, aeronautical engineers had a new frontier to challenge them. By the end of 1958, NACA had ceased to exist, replaced by the successor agency known as NASA. So it was that Langley became a Research Center and the de facto leader of the U.S. manned space program.



Inspecting a transport model between test runs in Langley's National Transonic Facility.

A group of veteran center researchers was organized into the Space Task Group (STG), which set to work to define and solve the problems associated with human spaceflight. In time, the group would originate the first designs for the Mercury space capsule and set up the nation's first space tracking network. The STG also organized a training program in Hampton for America's original seven astronauts. In the mid-1960s most of the Task Group moved to Houston to establish the new Manned Spacecraft Center, which eventually was renamed the Johnson Space Center.



A technician inspects new fan blades in the 16-foot Transonic Wind Tunnel.

In that same period Langley designed and managed the Lunar Orbiter Project, a highly successful program that mapped 99 percent of the Moon's surface in preparation for the manned lunar landings. The center also built simulators used by Gemini and Apollo astronauts to practice the spacecraft maneuvers that were critical to their missions.

The post-Apollo years didn't hit Langley as hard as it did some other NASA facilities. In the 1970s the center was given lead responsibility for the Viking Project, which culminated in two remarkably successful missions to the planet Mars. Langley researchers also spent much wind-tunnel time evaluating Space Shuttle designs, resulting in significant design improvements. By the 1980s, the center's Atmospheric Sciences Division was receiving international recognition for its innovative research; while on the space side, Langley scientists saw one of their prized creations, the Long Duration Exposure Facility (LDEF), launched and retrieved from orbit by the Space Shuttle. LDEF data continue to yield invaluable insights on the harsh environment of space. Today, Langley is hard at work on numerous projects, including studies of a next-generation supersonic aircraft, research into hypersonic flight and evaluation of technologies for the Space Exploration Initiative, a long-term program to send humans to the Moon and Mars.

After seven-and-a-half decades working at the leading edge of aeronautics and astronautics, the Langley culture still encourages the belief that, given talent, time and the right tools, anything is possible.

"The kinds of projects Langley has gone after have involved firsts like the Lunar Orbiter and Viking. That kind of success was unprecedented," says center director Holloway. "At Langley there still is a can-do attitude. Over the years the arguments haven't been over if we could do it; they were over how to do it."

The next NASA center may well be established in orbit, perhaps even on the Moon. But no matter what NASA's ultimate destination, it seems certain that Langley will continue to do what it has always done: figure out what works, then what works even better. •

Photos courtesy of the LaRC

James Schultz is a freelance writer who specializes in science and technology writing. He is the author of Winds of Change, *a 75th anniversary history of Langley, which is his third book. He also has written a contemporary history of Richmond, Virginia and a history of the rise to prominence of a southwest Virginia coal company.*

C-23.

The People Factory

A group from the U.S. Army Corps of Engineers surveys the future site of Langley Field in the fall of 1916, after considering 15 sites throughout Virginia and six other states.

Although Langley's many milestones in basic and applied astronautical research are likely to take center stage during this year's 75th birthday celebration, the center's most significant contribution to astronautics has little to do with machines or inventions.

"We talk an awful lot about technical accomplishments, and Langley certainly has had—and continues to have—its fair share of those," says center director Paul F. Holloway. "But Langley played a major role in another area that doesn't receive as much attention. It provided many of the leaders, both in industry and government, who went on to create this country's aeronautic and aerospace infrastructure."

Holloway points out that all of the early senior staff at other NACA centers came from Langley, and that people from Langley played a major role in getting the early space program going. "In my opinion," he says, "our biggest resource has always been a terrific group of people."

Many Langley "graduates" have gone on to distinguished careers in both the private and public sectors. Fred Weick, for example, led the Langley team that developed the nation's first streamlined engine cowling, and proposed the incorporation of the tricycle landing gear onto commercial aircraft. The "swept-wing" theories of Robert T. Jones proved invaluable to designers working on later-generation sub- and supersonic aircraft, while another Langley veteran, Richard T. Whitcomb, originated the Area Rule, a new concept in the shaping of high-speed aircraft, and invented the so-called supercritical (referring to any speed beyond the critical Mach number) airfoil to delay the drag rise that accompanies transonic airflows. Now retired, Whitcomb still lives in Hampton.

Langley researchers also made important contributions in the concerted national effort to get Americans into space. H. Julian "Harvey" Allen, who worked at the center through the late 1930s, eventually became chief of high-speed research at NACA Ames, where he devised a heat-dissipating blunt-body shape later incorporated into the design of space capsules.

Perhaps Langley's biggest contribution to the human conquest of space, however, was the 36-person Space Task Group (STG). Led by Robert R. Gilruth, the group included such pioneers as Maxime A. Faget, Caldwell C. Johnson and Christopher C. Kraft, Jr.. Although it later moved to Houston, the STG was the nucleus around which the entire U.S. manned space program condensed.

And it all began at Langley. •

For its 75th birthday the Langley Research Center commissioned a condensed history entitled *Winds of Change: Expanding the Frontiers of Flight*. This 140-page, coffee-table book contains numerous photos along with text that incorporates the comments of many past and present Langley employees. *Winds of Change* will be made available to the general public in July at the conclusion of Langley's anniversary observances. —*Editor*

Heavy

It's a rocket! It's a plane! No, actually it's a souped-up NASA hot rod.

by Les Dorr, Jr.

Think of NASA's great endeavors. Think of the stunning views of far-off planets, of Shuttle orbiters drifting over a clouddappled Earth. Think of exotic "X-planes" zooming over the California desert.

Think of the Little Old Lady From Pasadena.

The rock-and-roll epitome of lead-footed, triple-carbed, four-wheeled speed would feel right at home with NASA. Over the years, specially modified automobiles have done important space and aeronautics research for the agency. We're talking genuine, all-American heavy metal, some of the best and fastest that Detroit had to offer.

Back in 1962, NASA's Flight Research Center (today's Dryden Flight Research Facility) was preparing to test a new type of aerospace vehicle called the M2-F1 "lifting body." The piloted glider lacked wings. Instead, the underbody would create lift, a design that gave the tubby craft its name.

Wind tunnel tests predicted the shape should fly well, but center director Paul Bikle wouldn't let the M2 be hauled aloft by a tow plane until its handling qualities were better understood. He and lifting body pioneer Dale Reed brainstormed an alternative: Why not have a car pull the craft fast enough to get it airborne at low altitude, where it could be checked out with little risk?

Bikle tapped engineer Walt Whiteside, a self-described "fixit, go-get-it type," to find a suitable high-performance automobile. Whiteside got out his slide rule

Metal

and figured the speed and horsepower he would need, then called around to see what was available. He settled on a souped-up Pontiac Catalina convertible that was a real hot rod, even for those days when zero-to-60 performance was everything and the concept of good gas mileage was still years in the future.

"General Motors gave us a 421-cubic-inch, triple-carburetor engine like those on the Pontiacs running at the Daytona 500, a four-speed transmission and heavy-duty suspension and cooling systems," Whiteside recalls. "They also agreed to do it with no publicity. We were doing this kind of under the table, without talking to NASA Headquarters."

The center engineers took the "stock" Pontiac to a pair of high-performance auto shops, where it was fitted with a rearfacing seat, roll bar and special headers, then tuned for maximum horsepower. When the work was complete, Whiteside and NASA pilot Don Mallick did what they would do with any new research vehicle: They took it out on a series of check flights.

"We grabbed our clipboards and strapped on our helmets, then headed toward Boron (California) and Highway 395. Up that way there were plenty of 'measured miles' that we could use to calibrate the speedometer up to its maximum of 120 mph," says Whiteside. "That was also where we knew we'd find the fewest Highway Patrolmen."

After its break-in period, the Pontiac was ready for action. Whiteside remembers "nothing special" about towing the M2-F1

NASA's original "hot rod," this stripped-down 1962 Pontiac Catalina convertible was used as a tow vehicle for the M2-F1 lifting body–ancestor of today's Space Shuttle–at NASA's Flight Research Center (now Ames-Dryden Flight Research Facility).

into the air at 114 mph for the first time on April 5, 1963. No jokes, no unnecessary talk. NASA pilot Milt Thompson matter-of-factly called out his altitude, while Whiteside radioed the Pontiac's ground speed. The success of the first flight led to a routine test program; during the next four months, the M2 sailed behind the car on 100-plus flights (including a checkout hop for famed Air Force test pilot Chuck Yeager), with a total logged time of about four hours.

The white-and-yellow Catalina remained a familiar sight on the desert lakebed as it towed a variety of other piloted and unpiloted vehicles into the air, chalking up a total of 490 test runs. During the X-15 program, Whiteside often roared up and down the North Lake area in the car to make sure there were no obstacles to a safe landing by the rocket plane. He also acted as "photo chase" for NASA's B-52 mother ship, pacing the aircraft on its takeoff roll while a photographer snapped pictures from the "cockpit" of the Pontiac.

"The first time we took off, I wound up to around 130 mph," says Whiteside. "Then I looked back and the NASA photographer, Gene Childress, was just about plastered against the trunk! We never considered that he might need a safety harness to take the wind strain off him."

"We grabbed our clipboards and strapped on our helmets, then headed toward Boron and Highway 395....That was where we knew we'd find the fewest Highway Patrolmen."

By the late 1960s the Pontiac was tired out and headed for the "surplus" graveyard. But then it received one last call to NASA duty—this time, 3000 miles east.

Langley Research Center's Walt Horne was a zealot for pavement grooving—cutting thin slots in runway and highway surfaces to improve traction. To prove the concept, he did many high-speed automobile braking tests in the mid-1960s on a variety of wet and dry surfaces—grooved and ungrooved—at Wallops Flight Facility on the Virginia coast.

Horne and NASA researcher Tad Leland also had come up with a way to keep the test autos from spinning out on wet pavement. By installing brake line cutoff valves, they could brake only the wheels diagonally opposite from each other while the other two wheels rolled free. The result: A car that could maintain a straight line while taking data on tire friction.

Horne had used a diagonally-braked Ford Fairlane to study loss of tire friction ("hydroplaning") on wet surfaces. Later, he modified a Plymouth Fury station wagon from

NASA used a 1967 Plymouth Fury station wagon in pavement grooving and traction studies at Wallops Flight Facility.

the NASA motor pool with a similar setup. But the Plymouth's weight and plain vanilla engine made it a dog in the acceleration department, and it had already racked up high mileage before its conversion.

In 1968, Horne had the Flight Research Center's hot rod Catalina shipped to Langley, where he fitted it with diagonal braking. At Wallops, he did spinouts on a special "skid pad" to check the friction of several tire tread patterns on various surfaces at the request of the Virginia Highway Research Council. The test speeds were relatively sedate for the Pontiac—a maximum of 50 mph—although Horne admits that he once got the car up to "about 110" on the long Wallops runway.

The Pontiac's power and acceleration convinced Horne and Langley engineer Tom Yager that they should get a new, more dependable high-performance car for "Combat Traction," a joint NASA/Air Force braking study on 50 U.S. and European runways. Their choice was a natural "muscle car": a 429-cubic-inch 1969 Ford XL coupe.

Besides adding a roll bar for safety, Horne and Yager left the Ford pretty much alone. They did add an anti-skid braking system to the front wheels—the top-of-the-line Ford already had it on the rear—because planes normally had such equipment. Horne soon found that early automotive anti-lock brake technology wasn't quite up to the job, however.

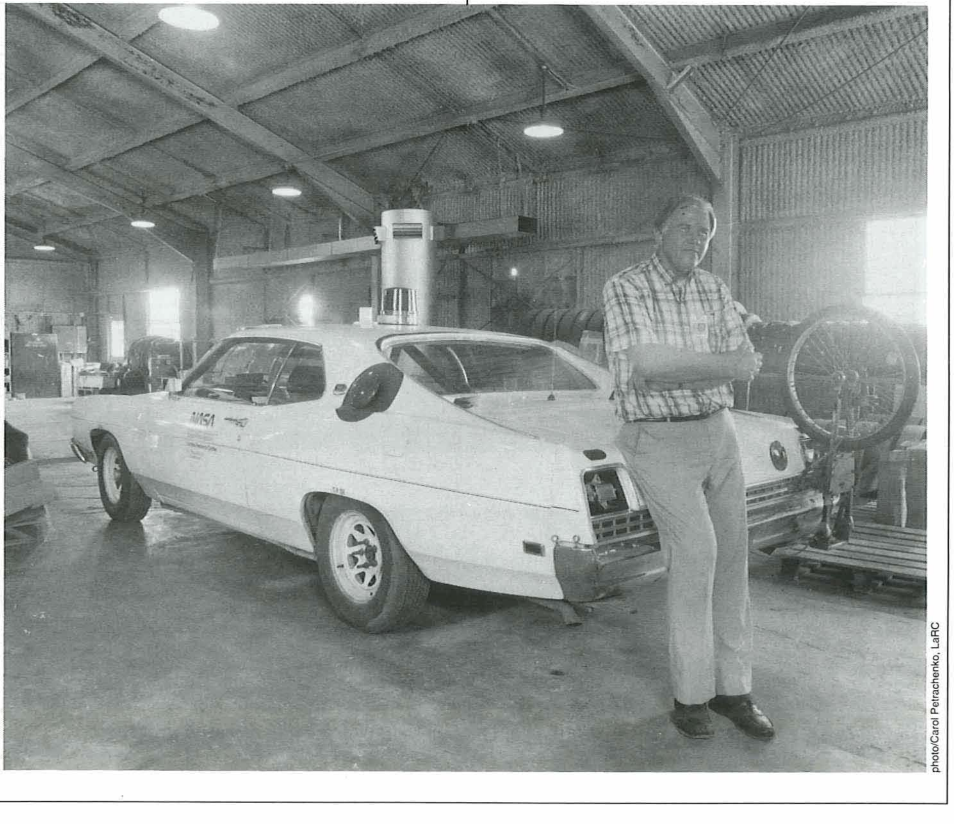
"I tried the system out at Wallops before we went to Europe," Horne remembers. "It worked in stops from 20, 30, up to 60 mph. But at 70, the rear wheels locked up and the car swung around. I ended up rolling backward down the runway at high speed. I finally had to slow down by putting on the gas!"

"That was the end of the anti-lock system," adds Horne. "We went back to diagonal braking."

The 1968-69 Combat Traction tests were only the start of the Ford's NASA career. Thousands of times over the next 23 years, the car did braking runs on runways around the world. Yager recounts a standard test procedure that sounds like those performed by NASA research pilots:

"I'd turn on the recorder and make sure the seat belts and shoulder harness were fastened. Then I'd mash down the accelerator and get up to 65 mph. A couple hundred feet before the test section, I'd throw the car into neutral, then aggressively apply the brakes as I entered it. When I came to a stop, I manually recorded the stopping distance off a meter on the dash and flipped the recorder off."

The point of using a diagonally-braked car in the NASA tests was to develop a way to forecast aircraft braking performance under various weather conditions. For the first several years, the Langley researchers painstakingly analyzed "friction-speed curves" developed from data



Above, a 1969 Ford XL is used as a noise source for instrument calibration; right, Langley engineer Tom Yager with the Ford which still serves NASA at Langley.

photo/Carol Petrachenko, LaRC

taken by the Ford and several specially instrumented planes. By 1973, says Horne, they felt they "had a good handle" on being able to predict how well aircraft could stop on dry, wet and snow-covered runways.

During the 1970s, the Ford XL took friction readings at airports and Air Force bases where officials suspected rubber contamination from aircraft tires was building up, or where skidding accidents had occurred on wet runways. In 1978, Yager and the car headed west to support a National Transportation Safety Board accident investigation. A DC-10 airliner had blown a tire on takeoff and crashed into the runway approach lights at Los Angeles International Airport.

"We got measurements on the runway and were able to relate them back to the actual black box [flight recorder] data from the DC-10. The readings from the plane agreed with the tire friction performance predicted by the diagonally-braked vehicle," says Yager. "Since then we've looked at about 20 more wet runway skidding accidents using that technique."

When the Space Shuttle was ready to start landing tests in 1977, NASA called on the Ford to pave the way. The car made hundreds of test runs across the dry lakebed near Dryden to identify any soft spots and find out how much traction the surface would provide. Later, the car took friction readings on the gypsum runways at White Sands Space Harbor in New Mexico and on the 15,000-foot concrete runway at Kennedy Space Center in Florida—information eventually used to formulate some of the Shuttle's landing rules.

Langley's Ford still soldiers on doing NASA research. In May, for example, the car returned to Wallops for tests of a Czech friction unit marketed by a California company. Future tasks include studies of how anti-snow and ice chemicals affect runway friction, as well as tests to help define the effect of natural rainfall on traction.

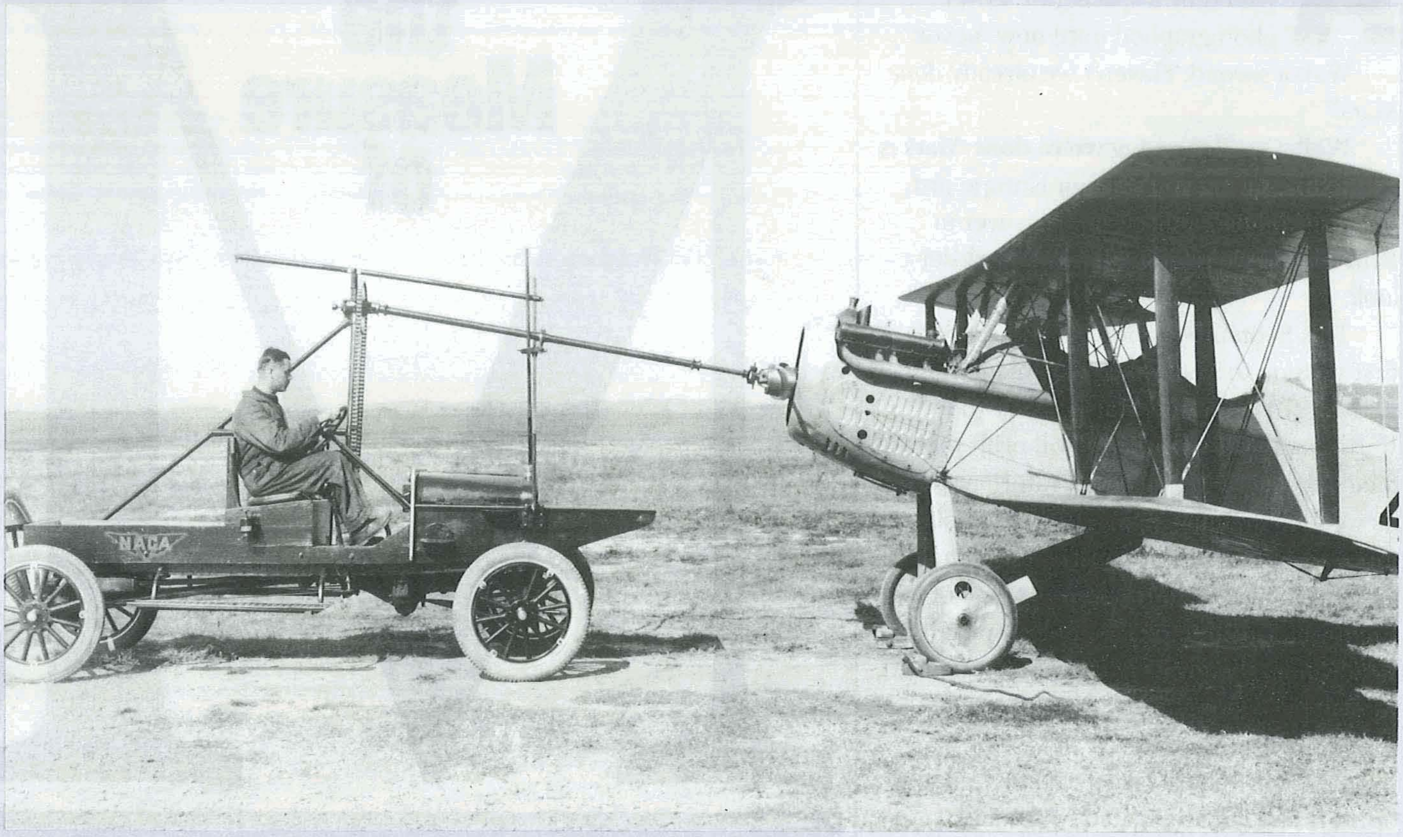
Even with only 46,000 miles on its odometer ("Probably the least for any 1969 Ford in the country," Yager chuckles), the Ford's time may be running out. Advances in aircraft computers and electronics make it possible to write programs that can display braking performance for pilots in real time, eliminating the need to estimate it with a ground vehicle. But Tom Yager isn't ready to trade his gas pedal for a computer screen just yet.

"Knowing the things we've gone through over the years just to get people to recognize the reasons to monitor runway friction," he says, "I suspect that's going to be easier said than done." •

Les Dorr last wrote for the magazine about high-speed aircraft research.

Today, the Ford XL "muscle car" is still part of Langley's runway friction research program.

The Detroit Connection



A modified Ford Model A used to start aircraft propellers, circa 1931.

When NASA's SR-71 "Blackbirds" get ready to fly at Dryden, a deafening roar booms across the concrete runway apron—not from the jets themselves, but from two 454-cubic-inch Chevy V-8s in the "starter cart" that ground crews use to crank up the planes' engines.

The SR-71 ground equipment is just the latest way that NASA and its predecessor, the National Advisory Committee for Aeronautics (NACA) have put off-the-shelf automotive technology to work in aeronautics and space research programs. Some other examples:

A modified Ford Model A truck served as an aircraft starter in the early days of flight research at Langley. A shaft connected to a plane's propeller turned over the engine.

In the late 1930s, Langley researchers used a 1938 Chevrolet fitted with an aerodynamic fairing to haul gliders into the air. The tests produced data on the ground effects of towed gliders.

An airtight 35-foot-long Airstream travel trailer was home to several Apollo crews for the first 65 hours after they returned from the moon. The converted trailer cocooned the astronauts so that doctors could sniff out possible lunar germs.

From the mid-1970s to the late 1980s, the engine, front-wheel-drive and frame of a 1973 Oldsmobile Toronado pulled airplane models through Langley's Vortex Research Facility. The engine, beefed up with improved carburetion and racing parts, churned out about 500 horsepower.

A subscale F-15 robot research plane arrived at Dryden sans landing gear in 1972. Resourceful NASA engineers scratchbuilt the gear, including auto shock absorbers bought at the nearest Sears department store.

Before and after its 69-month stay in space, NASA's Long Duration Exposure Facility (LDEF) satellite was assembled and hauled around in a transporter made from two Fruehauf truck trailers that had been chopped apart and welded together to make a single carrier. —*Les Dorr, Jr.*

Taking the Measure of M

Ah, Mars, the Red Planet. Shrouded in ancient mystery, never before visited by a spacecraft, never photographed until now, never…

Wait a second. Haven't we already *done* Mars?

Well, yes. But saying we've done Mars is a little like saying you've seen Europe just because you had a three-hour layover in Brussels. So we're going back for a closer look.

This September, the U.S. will send its first mission to Mars since the Viking project of the 1970s. For one Martian year (687 Earth days) Mars Observer will orbit the planet, collecting a wealth of information on its weather systems, magnetic field, global topography, surface chemistry and mineralogy. As Project Scientist Arden Albee of the California Institute of Technology puts it, "We will not be just *exploring* Mars. Instead, we will be systematically *observing* Mars over an entire Martian year."

It's been 16 years since the two Viking orbiters and landers visited Mars, and planetary scientists have pretty much gleaned what they can from poring over the same old data again and again. "There are some things we say we 'know' from Viking," says Albee, "but we only know that from the basis of one observation."

Mars Observer will have the huge advantage of continuous, long-term coverage—much as Earth-orbiting satellites keep year-round watch over our own planet. In fact, says Albee, "The approach is very much like EOS [the Earth Observing System]. We're trying to get these basic data sets—not to answer specific questions necessarily, but to be able to answer a whole host of different kinds of questions, some of which you can't even pose at the moment."

The mission, which is managed by the Jet Propulsion Laboratory, is scheduled to get underway on or about September 16 (the launch window lasts 24 days) when Mars Observer will be launched on a Titan III commercial launch vehicle from Florida. Attached to the spacecraft will be a Transfer

by Tony Reichhardt

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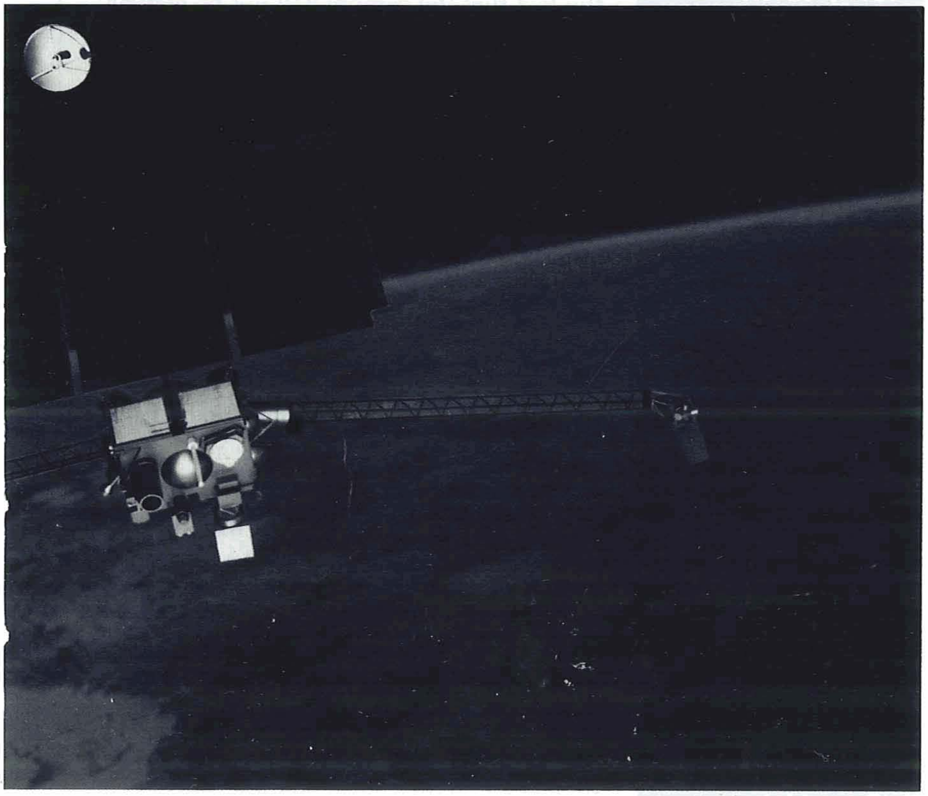
Mars Observer goes for the Big Picture



Orbit Stage (TOS) built by Orbital Sciences Corporation, which will mark the first use of this commercial upper stage.

After an 11-month cruise through interplanetary space, Mars Observer arrives at its destination in August 1993. At first its orbit around the planet will be high and elliptical. Gradually this will be adjusted to a near-circular, near-polar mapping orbit approximately 250 miles above the Martian surface. The orbit will be sun-synchronized, meaning that sunlight will be coming from the same angle throughout the mission.

Each day the spacecraft will return images from its digital cameras as well as data from its other onboard sensors (see "What's Onboard"). The philosophy of the mission, says Albee, is to have all these different instruments working in concert, building up a comprehensive portrait of a world. "It's not that any one instrument is probably going to make a discovery," he says. "What we're going to have are these synergistic data sets."

For example, scientists would like to better understand the seasonal variations in the Martian polar caps, which are made primarily of carbon dioxide. The ice caps expand in the cold of Martian winter and shrink due to melting in the summer when it's warmer. "This is a tremendous change," says Albee, "like the ice ages on Earth. The amount of material being transferred [between the surface and the atmosphere] is just incredible." By tracking that transfer of material with several different instruments, Mars Observer will in effect be watching one of the planet's "life processes" in action.

The nature of magnetism on Mars is one puzzler that this mission could help to solve. The planet's magnetic field is known to be very weak, and may not even exist at the present time. "Everything we know about the geology argues that if it isn't there now,

After being boosted out of Earth orbit by a Transfer Orbit Stage (opposite page), Mars Observer will arrive at Mars in August 1993.

it must have been there not too long in the past," says Albee. The onboard magnetometer will search for direct evidence of an existing field, while the electron reflectometer looks for subtler historical clues: Even if there is no magnetic field today, the instrument may be able to detect remnant fields in surface rocks that were formed in the geologic past.

Another nagging question is whether there is or ever has been water on the surface of Mars. "Since Viking, our ideas on water on Mars have gone back and forth like a pendulum," says Albee. "First there was abundant evidence for it, then we said, 'Gee there isn't any water there.' And now we figure there's got to be water—it must be under the surface." Mars Observer should help clear up the mystery. While the gamma ray spectrometer searches for traces of hydrogen, high-resolution pictures from the camera may show permafrost or channel features that reveal how much water once flowed on the surface, and when.

Ironically, adding the Mars Observer camera was an afterthought to the original mission plan. As the first of the new Planetary Observer class of spacecraft, the project is designed to be modest in scope and relatively cheap. That meant that "If [the camera] had any chance of being chosen, it had to be very, very simple," says Albee.

The solution was to build a camera with no moving parts. "It doesn't have a shutter, it doesn't have movable mirrors. It's controlled basically by opening it up and taking data, and then editing the data," says Albee. The resolution of the pictures depends only on how much information is extracted from the raw images and then sent down to the ground—an editing job that will take place inside a powerful onboard processor. "The camera by itself has more computing power and more memory than all the spacecraft JPL's ever flown put together," says Albee.

During the mission the camera will return a low-resolution image of the whole planet each day, in much the same way that weather satellites do for Earth. Moderate resolution (down to about 300 meters) images will be less frequent, but will still provide global coverage many times over by the time the mission is finished.

The primary mission will last one Martian year—687 Earth days.

Mars Observer will have the huge advantage of continuous, long-term coverage — much as Earth-orbiting satellites keep year-round watch over our own planet.

The high-resolution imagery is where Mars Observer's camera will really shine. Viking and Mariner have photographed the entire surface of Mars at a resolution of 250 meters, which is about equivalent to Mars Observer's moderate resolution. But at 100 meters resolution, the earlier missions only covered about 15 percent of the planet. And at 20 meters, the coverage drops down to a paltry two-tenths of a percent. Mars Observer's narrow-angle views will beat that resolution by nearly a factor of ten, with each picture element, or pixel, representing 1.4 meters on the surface, given the spacecraft's altitude of 250 miles.

These highest resolution images will be relatively few and far between, however: Buffer space on the onboard processor won't allow more than one such picture per orbit. Targeting these highresolution photos will be no mean trick, either, given the uncertainties of orbital position and timing and the fact that the camera will not be actively controlled or pointed.

But the payoff could be enormous. Two targets of particular interest will be the Viking landing sites in Chryse and Utopia, where a pair of now-dormant robots still stand where they touched down 16 years ago in the windswept plains. The landers themselves will be only pinpoints in the images, but high-resolution pictures of the surrounding area would be fascinating to compare with photos of the landing sites taken from the ground more than a decade ago.

"From a science point of view, it's really important to get that image of the Viking lander sites because we have data from the surface," says Albee. "So we're going to work like hell to get it."

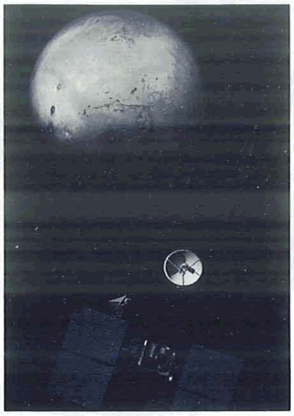
Still, the camera was designed for global, systematic mapping coverage rather than very precise pointing. Can we guarantee that we'll get a picture of the landing sites? "The answer is no," says Albee.

Other high-resolution images are planned not for specific objects so much as selected kinds of terrain—dune fields, for example, or ancient water channels, or the layered geology around Mars' polar caps. In addition, says Albee, "You would clearly like some high-resolution images of the slope of Olympus Mons— not any one particular spot, but samples to see how to interpret it."

Late in the Mars Observer mission, from September 1995 to February 1996, the spacecraft may also get the chance to collaborate with an international "partner." If the Russian-led Mars '94 mission comes off as planned, it will carry a clever and ambitious French-designed experiment to explore the Martian surface with specially instrumented balloons. Onboard Mars Observer will be a radio relay—supplied by the French Centre Nationale d'Etudes Spatiales—that will receive signals from these instruments on the ground. The data will then be formatted by Mars Observer's powerful onboard processor for transmission to Earth.

With imagery and other data from Mars Observer flooding back to Earth daily throughout the nearly two-year mission, the scientific investigators will have a very different job than they did for past planetary encounters like Voyager and Pioneer. For those fly-bys, the scientists would all gather in Pasadena during a single intense period of science return. For Mars Observer, rather than the scientists going to the data, the data will come to them. All the mission's principal investigators will be equipped with their own computer work station where they can receive data from the spacecraft and update commands to be sent to their own instrument, all without ever having to leave home. As a result, says Albee, "We have a much leaner operations group than we would ever have had in the past."

Mars Observer and Magellan represent a new generation of planetary missions where the emphasis is not so much on discovery as on close examination and deeper understanding. These missions are less dramatic, perhaps, than Voyager's and Viking's first looks, but their scientific return is much richer. Which means that by the time Mars Observer finishes its business sometime in the mid-1990s, planetary scientists won't any longer be forced to drag out their old Viking photos when you ask them what's new on Mars. •



Mars Observer: Painting a detailed portrait of a world.

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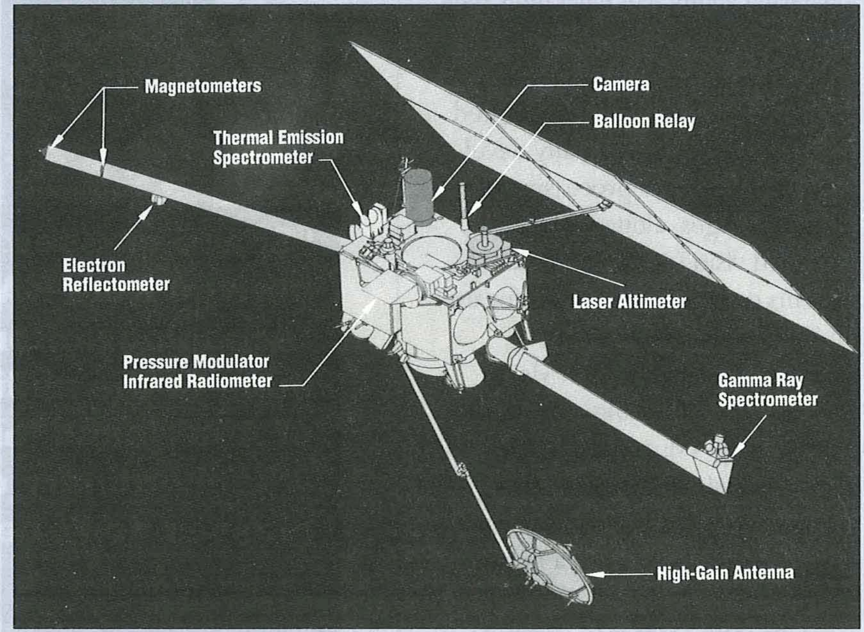
Tony Reichhardt is a freelance writer based in Washington, D. C.

What's Onboard



Mars Observer will carry a total of seven science instruments:

The **Mars Observer Camera** will take digital images in high-, medium-, and low-resolution modes.

A **Gamma-Ray Spectrometer** will measure the abundance of elements on the Martian surface, including iron, silicon, uranium, and hydrogen—the latter of which could provide clues to the presence of water ice.

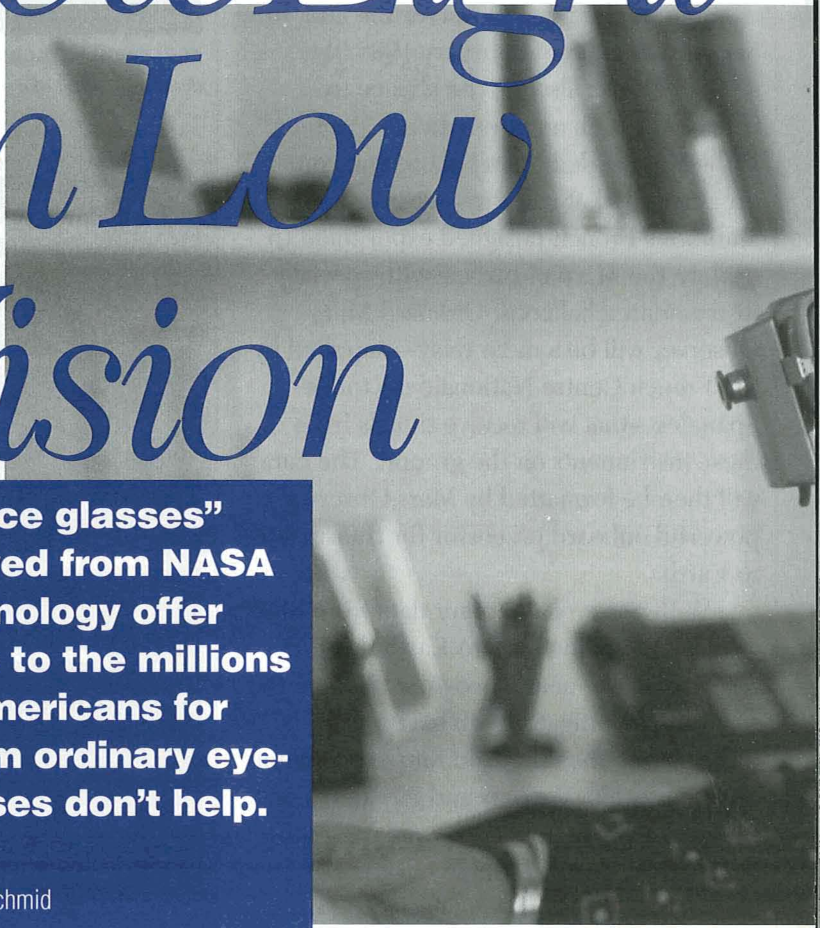
The **Thermal Emission Spectrometer** will map minerals and temperatures on the surface, as well as return information on cloud composition.

While a **Laser Altimeter** determines topographic relief, tracking data from the spacecraft's radio will measure the Martian gravity field. The radio also will be used to build up a temperature profile of the atmosphere.

The **Pressure-Modulator Infrared Radiometer** will observe the mixing of dust, ice, water vapor, and other constituents of the atmosphere at different latitudes and longitudes as it changes throughout the Martian seasons.

A **Magnetometer** and **Electron Reflectometer** will measure the magnetic field and determine how it interacts with the solar wind. •

Shedding New Light on Low Vision



"Space glasses" derived from NASA technology offer hope to the millions of Americans for whom ordinary eyeglasses don't help.

by Beth Schmid

One of the most poignant memories from 1992's Winter Olympics was the sight of ice skater Nancy Kerrigan's mother, straining to see her daughter give the performance of her life to win a medal for the United States. Quite possibly Nancy's effort to win the bronze was exceeded only by her mother's effort to witness her triumph.

Soon, thanks to a NASA/Johns Hopkins University Wilmer Eye Institute cooperative effort called the low vision project, the approximately three million Americans suffering as Mrs. Kerrigan does from low visual acuity will have high-tech help.

Scientists from the Stennis Space Center and Wilmer adapted NASA technology originally developed for computer processing of satellite images, along with head-mounted vision enhancement systems originally generated for use on Space Station Freedom, to improve the seeing of low vision patients. By enhancing and altering the TV images displayed inside specially designed goggles, this technology will enable patients with impaired eyesight to live a more normal life.

Low vision refers to chronic, disabling eye impairments that are uncorrectable with traditional glasses, contact lenses or eye surgery. About 800,000 Americans with low vision are categorized as legally blind, meaning that they have vision worse than 20/200 in the better eye, even while wearing corrective glasses or lenses. Yet more than 80 percent of those who are legally blind retain some vision.

The low vision system, which will "remap" distortions in the eye to compensate for degradation of the retina or other impairments, consists of a pair of wrap-around "space glasses" and a portable computer. Mounted in the glasses are one or more cameras, along with display screens and an eye tracker. When a patient looks at an object appearing in the video image in front of their eyes, the cameras "look" wherever the eyes look.

The cameras then send the image to a computer-based system located in a small pack worn around the waist. The computer's software, which is tailored to the patient's specific visual problem, manipulates the image and sends it back to be displayed on small video screens in front of each eye.

"Instead of looking through ground glass, you will be looking through a computer," says Doug Rickman, the NASA Low Vision Project manager at Stennis.

The prototype of the space glasses weighs 22 ounces, but the

Stennis's low vision project manager Doug Rickman models the space glasses.

weight is expected eventually to drop to about a pound. The system currently "sees" in black and white; color would require more visual data and would be much more expensive. When the space glasses become commercially available—in the fall of 1993, according to current plans—they are targeted to cost in the neighborhood of $4000.

Although that might sound prohibitive, it seems like a good deal when you consider the other aids for low vision that are now available. To date, the standard treatment for patients suffering from low vision has been to use various methods to magnify images, making them more detailed and providing more contrast.

"Instead of looking through ground glass, you will be looking through a computer"

Some low vision patients carry a whole array of magnifiers wherever they go, just to be ready for any circumstance, according to Rickman. There are glasses with telescopic lenses for close-up work like painting or reading, and there are videoscreen print magnifiers. Closed-circuit TV—a 30-year old technology—provides one of the only ways for some patients to read or write at all.

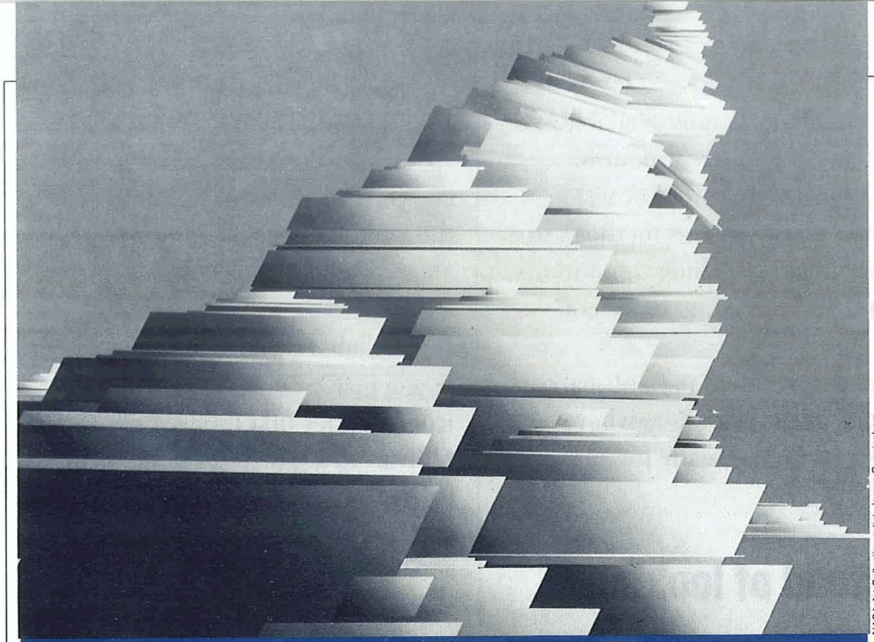
Robert Massof of the Hopkins' Wilmer Eye Institute says that one of the most common complaints of low vision patients is that they cannot distinguish faces properly. "Faces can appear to be blank, with little or no recognizable features." There are other frustrations: Patients may be able to read the title of a book but not the story, or to see tennis players but not the ball. Rickman says that the white paper and black print used by most newspapers and magazines also pose a problem for low vision patients, whereas "If the paper were black and the print white, they would be able to function much better; it would provide better contrast." The space glasses, with their onboard computer processing, could reverse the white and black on the page, allowing the patient to see more easily.

Collaboration on the project began in 1985 when representatives from Wilmer first met with NASA officials to see if they knew of any technology that could help in the institute's work to enhance visual acuity. NASA's Office of Commercial Programs' Technology Transfer Program asked Stennis, with its considerable expertise in the design, fabrication, integration and operation of space sensor systems, to be NASA's lead center for the effort. That's when Doug Rickman, a geologist working in the field of satellite image processing, was asked to manage the project. And asked. And asked again.

Rickman explains it like this: "For various reasons, I turned down the offer to work on the low vision project twice. Then, one Sunday morning in church, the preacher read the story in the Bible about the loaves and fishes; about how someone in the hungry group said there were too many people and not enough food to feed them all. About how it all worked out okay in the end. The preacher said that sometimes we are called upon to do more than we think we can do. I felt I was getting a special calling. It convinced me to take on the project."

And now, Rickman says, he's glad that he did. "This is what we call an enabling technology. It will have an impact far beyond this one application." •

Photos courtesy of Bill Ingalls, NASA Hq., and Johns Hopkins Lions Vision Center.



NASA Art Collection artist, James Cunningham

A Defining Moment

by James A. Michener

Renowned novelist James Michener voiced the following thoughts about the exploration of space in his April 28 testimony before the House Committee on the Budget. —*Editor*

Throughout my career, I have given more than a little study and more than a little thought to the patterns of prosperity and decay which have characterized great nations and dominant cultures. I believe destinies are frequently shaped by a "defining moment," and by a society's ability to recognize and capitalize on that moment. I would place in this pantheon Sigmund Freud's analysis of human behavior and Karl Marx's dissection of production and distribution. For any nation to have missed the significance of these powerful movements was to have missed the meaning of contemporary history.

"...I believe that there are moments in history when challenges occur of such a compelling nature that to miss them is to miss the whole meaning of an epoch. Space is such a challenge."

Certainly, the world was changed by that cascade of brilliant industrial inventions produced by England in the late 1700's and early 1800's. We live today on the consequences of that industrial revolution. And I would include our own nation's enviable capacity to finance, organize and manage large industrial corporations.

But history is a grand mix of concepts, actions, organizings and commitments which determines the extent to which any nation can achieve a good life for its citizens. And I believe without question that if a nation misses the great movements of its time it misses the foundations on which it can build for the future.

One word of caution. I am not here speaking of either fad or fashion. I am not extolling the attractive ephemeral. And my experience in the arts has taught me to be suspicious of late fashions or high styles.

But I also believe that there are moments in history when challenges occur of such a compelling nature that to miss them is to miss the whole meaning of an epoch. Space is such a challenge. It is the kind of challenge William Shakespeare sensed nearly four hundred years ago when he wrote:

> "There is a tide in the affairs of men, which, taken at the flood, leads on to fortune; omitted, all the voyage of their life is bound in shallows and in miseries. On such a full sea are we now afloat, and we must take the current when it serves, or lose our ventures."

The space program—perhaps as was crystallized in the moment of Neil Armstrong's epochal "small step"—is the one colossal achievement which may well define our culture much in the way that the pyramids do that of ancient Egypt. We risk great peril if we kill off this spirit of adventure, for we cannot predict how and in what seemingly unrelated fields it will manifest itself. A nation which loses its forward thrust is in danger, and one of the most effective ways to retain that thrust is to keep exploring possibilities. The sense of exploration is intimately bound up with human resolve, and for a nation to believe that it is still committed to forward motion is to ensure its continuance. Your challenge, the test of your leadership, and I believe the scale with which history will measure your wisdom and insight, is whether you make these achievements a part of a continuum—not merely an historical oddity. To turn away from these initiatives, wholly or in part, from the point of view of a historian, is unthinkable—particularly at a time when the real dividends of space research are only just becoming within reach.

I doubt if there is a woman or man in this room who honestly believes that the United States could ever fall backward, as other nations have within our lifetime. Intuitively, we feel that we are exempt. Yet for us to think so is to fly in the face of all history, for many nations at their apex were inwardly doomed because their will power had begun to falter, and soon their vulnerability became evident to all. Enemies do not destroy nations; time and loss of will bring them down.

Therefore, we should be most careful about retreating from the specific challenge of our age. We should be reluctant to turn our back upon the frontier of this epoch. Space is indifferent to what we do; it has no feeling, no design, no interest in whether we grapple with it or not. But we cannot be indifferent to space, because the grand slow march of our intelligence has brought us, in our generation, to a point from which we can explore and understand and utilize it. To turn back now would be to deny our history, our capabilities.

Each era of history progresses to a point at which it is eligible to wrestle with the great problem of that period. For the ancient Greeks it was the organization of society; for the Romans it was the organization of empire; for the medievalists the spelling out of their relationship to God; for the men of the 15th and 16th centuries the mastery of the oceans; and for us it is the determination of how mankind can live in harmony on this finite globe while establishing relationships to infinite space.

"The sense of exploration is intimately bound up with human resolve, and for a nation to believe that it is still committed to forward motion is to ensure its continuance."

My life changed completely on the day I saw the Viking photographs from the surface of Mars, for I had participated in that miracle. My tax dollars had helped pay for the project. The universities that I supported had provided the brains to arm the cameras. And the government that I helped nourish had organized the expedition. I saw the universe in a new light, and myself and my nation in a new set of responsibilities. My spirit was enlarged and my willingness to work on future projects fortified.

No one can predict what aspect of space will invigorate a given individual, and there must have been millions of Americans who did not even know Mars had been photographed.

But we do know that in previous periods when great explorations were made, they reverberated throughout society. Dante and Shakespeare and Milton responded to the events of their day. Scientists were urged to new discoveries. And nations modified their practices.

We all recognize the hard choices the Congress must make, and the need to address federal deficits and social needs. But as certainly as there are pressing needs of the day, the needs of the future will surely be far more desperate if we do not prepare for them today. To prosper, our children and grandchildren will need new jobs in new technologies, new challenges, and new worlds to conquer. We have no mechanism which transmits this legacy more effectively than our civil space program. All the thoughts of men are interlocked, and success in one area produces unforeseen successes in others. It is for this reason that a nation like ours is obligated to pursue its adventures in space. I am not competent to say how much money should be spent. I am not competent to advise on how the program should be administered. But I am convinced that it must be done. •

Ames

Visitors from the East

A trio of U.S. Senators—John Seymour of California, Ted Stevens of Alaska and Pete Domenici of New Mexico—traveled to Ames last April to tour the center's National Full-Scale Aerodynamic Complex (NFAC). Guided by Fred Schmitz, director of the NFAC, along with center director Dale Compton and deputy Vic Peterson, the senators viewed the world's two largest wind tunnels, which are housed in a facility that has played a key role in the testing of every major advance in U.S. aeronautical and spacecraft design since World War II.

Dale Compton, far right, points in the motor blade area of the wind tunnel during a tour; also pictured from left are Fred Schmitz, Senator Seymour and Senator Stevens.

Seymour praised NASA and Ames for their comprehensive technology transfer programs and for their success in encouraging and developing small and minority businesses. He also took time to chat with a group of children who had completed a day visit to the Ames Aerospace Encounter, a new program dedicated to showing young students the wonder and fascination to be found in science, technology, and mathematics. •

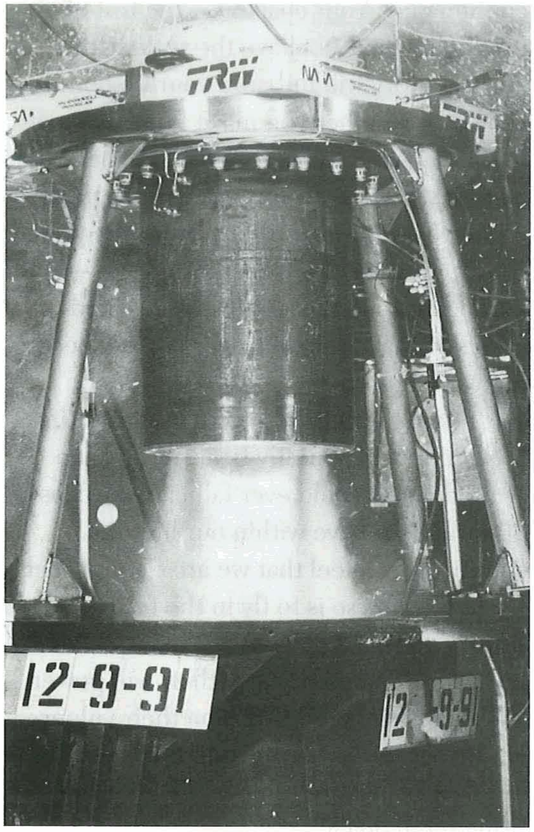
Marshall

Casting Around

Three Marshall labs—the Propulsion Lab, Structures and Dynamics Lab, and Materials and Processes Lab—are using the latest manufacturing technology to design and build an advanced prototype main combustion chamber for future rocket engines. One process being studied is investment casting, which uses wax representations of the part to be manufactured to build up a ceramic mold. The mold is then baked and hardened and the wax is melted out, leaving a cavity in which molten metal is poured. The mold shell is then removed from the metal part.

With current production methods, there are dozens of welded parts in a combustion chamber's main structure that require inspection. With investment casting, the hope is to create essentially a one-piece structure. Not only would this be less expensive, it would cut production time significantly and make inspection easier. •

Lewis



Lewis/TRW successfully test a low cost rocket engine.

Keep It Simple

The Lewis Research Center and TRW Space & Technology Group have successfully completed the first phase of a testing program intended to show that costly high-performance engine components can be replaced by cheaper, simpler technology that still meets mission requirements. The work is part of a cooperative agreement to test concepts developed during TRW and McDonnell Douglas trade studies of low-cost expendable commercial launch vehicles.

The engine tests—known as the Low Cost Liquid Oxygen/Liquid Hydrogen Rocket Engine Demonstration Program—involved firing a 16,500-pound thrust engine at Lewis's Rocket Engine Test Facility. The tests successfully demonstrated the feasibility of using a low-cost injector similar to one used for the Apollo lunar lander descent engines, as well as a low-cost ablative combustion chamber liner. The higher than expected performance, excellent stability, and durability of the ablative material proved that this is an exciting engine concept that may help to lower the cost of access to space. •

Ames-Dryden

International Flyers

Test flights of the X-31 Enhanced Fighter Maneuverability demonstrator aircraft resumed at Ames-Dryden in April. Test pilots are investigating the use of thrust vectoring (directing engine exhaust flow) coupled with an advanced flight control system for close-in air combat at very high angles-of-attack. "Angle-of-attack" describes the angle of an aircraft's body and wings relative to its actual flight path. In combat maneuvers, pilots often fly at extreme nose-high angles while the plane continues to go forward, but at high angles-of-attack a pilot can lose control of the aircraft.

The X-31 international test organization (ITO) is conducting the flight tests at Ames-Dryden to collect data that may apply to highly-maneuverable next-generation fighters. During the next year, an international team of pilots will make as many as 20 test flights a month with each X-31. The planes will then be used for military utility evaluations at the Naval Air Test Center at Patuxent River, Maryland, beginning in early 1993. •

Langley

Celebrating the Past

The Virginia Air and Space Center and Hampton Roads History Center opened in Hampton, Virginia, on April 5 to an overflow crowd of 12,000 people. Virginia Governor L. Douglas Wilder said at the grand opening: "Virginia has been a pioneer in aeronautics, [with] the first American aeronautical research laboratory, our nation's first Air Force base, the birthplace of the space program, and today the continued research and application of aerospace technology at the NASA-Langley Research Center." NASA's Associate Administrator for Aeronautics and Space Technology, Richard (Pete) Petersen, also attended the opening, saying, "We plan to make this the best aerospace educational center in the nation. While NASA will help with all aspects of the museum, we will pay special attention to the needs of students and teachers and the education which is being put together by the museum and the NASA staff." •

photo/Fred Jones, LaRC

Virginia's governor L. Douglas Wilder at podium; NASA's Richard "Pete" Petersen is pictured at far left.

Goddard-Wallops

El Coqui

Add Puerto Rico to the list of NASA launch sites: Wallops has established a new launch range on the island's northern coast west of San Juan. The range recently was used for the first time for Project El Coqui (named after a kind of tree frog found in Puerto Rico), a NASA sounding rocket campaign to study the ionosphere, which runs from May 17 to July 13. Scientists from universities, NASA, and other government agencies are studying how the ionosphere responds to artificial perturbations in order to learn more about how it is naturally perturbed. The ionosphere is of interest since it reflects high-frequency radio waves and disturbs satellite signals that pass through it. Students from the University of Puerto Rico at Mayaguez also participated in the project through grants from the Goddard and Marshall Space Flight Centers. •

Goddard

Solving an Old Mystery

U. S. scientists have solved the mystery of Geminga—one of the brightest emitters of high-energy gamma rays in the sky. Geminga, first discovered 20 years ago, had continued to baffle scientists who were unclear about the source of its power and why it shines brightly in gamma rays. Using data from both the Roentgen and Compton Gamma Ray Observatory satellites, scientists from Goddard and Columbia University announced in May, that Geminga's power plant is a rotating, 300,000-year-old neutron star. The scientists observed x-ray pulsations from Geminga that firmly established it as a close cousin of the Crab and Vela nebulae, which also have pulsating neutron stars at their cores. This discovery not only explains the nature of Geminga, but suggests that many of the remaining unidentified gamma ray sources in the Milky Way galaxy also may be neutron stars. The ROSAT and Compton observatories will search for additional members of this emerging class of gamma ray pulsars. •

The more things change, the more they stay the same. In the 1950s, rocketry pioneer Wernher von Braun envisioned a space station that was remarkably similar in spirit and purpose to the station NASA is building today. "Development of the space station," he wrote, "is as inevitable as the rising of the sun."

This year marks the 40th anniversary of Wernher von Braun's provocative series of articles written for *Collier's* magazine on the future of the space program. In honor of the occasion, we're reprinting the following excerpts from "Crossing the Last Frontier," published in *Collier's* on March 22, 1952. Even though von Braun's spinning, wheel-shaped concept differed in many of its technical details from today's configuration, many of his ideas about building a space station were ahead of their time, and they still ring true today. *—Editor*

A Companion in the Skies

by Wernher von Braun

"....Within the next 10 or 15 years, the Earth will have a new companion in the skies, a manmade satellite that could be either the greatest force for peace ever devised, or one of the most terrible weapons of war, depending on who makes and controls it. Inhabited by humans and visible from the ground as a fast moving star, it will sweep around the Earth at an incredible rate of speed in that dark void beyond the atmosphere which is known as 'space'...."

"....In the opinion of many top experts, this artificial moon— which will be carried piece by piece by rocket ships—will travel along a celestial route 1,075 miles above the Earth, completing a trip around the globe every two hours...."

"....When man first takes up residence in space, it will be within a spinning hull of a wheel-shaped structure, rotating around the Earth much as the moon does. Life will be cramped and complicated for space dwellers. They will exist under conditions comparable to those on a modern submarine...."

"....Besides its use as a springboard for the exploration of the solar system, and as a watchdog of the peace, the space station will have many other functions. Meteorologists, by observing cloud patterns over large areas of the Earth, will be able to predict the resultant weather more easily, more accurately, and further into the future. Navigators on the seas and in the air will utilize the space station as a 'fix,' for it will always be recognizable...."

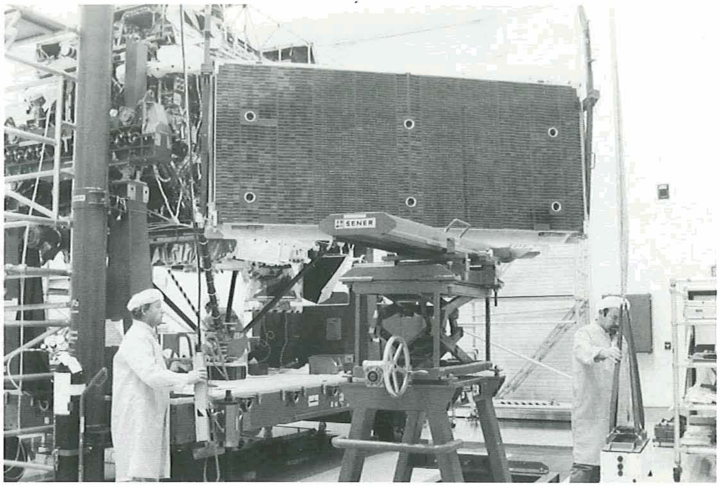
"....The space station's crew will be able to see glaring white patches of overcast reflecting the light of the sun. The continents will stand out in shades of gray and brown bordering the brilliant blue of the seas. North America will look like a great patchwork of brown, gray, and green reaching all the way to the snow-covered Rockies. And one polar cap—which happens to be enjoying the summer at the time—will show as a blinding white, too brilliant to look at with the naked eye...."

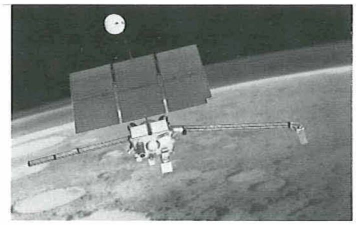
"....Development of the space station is as inevitable as the rising of the sun; man has already poked his nose into space and he is not likely to pull it back....."

"....There can be no thought of finishing, for aiming at the stars—both literally and figuratively—is the work of generations, and no matter how much progress one makes, there is always the thrill of just beginning...." •

UPCOMING LAUNCHES

- STS-46—the Space Shuttle Atlantis will deploy the European Retrievable Carrier (EURECA) and the Tethered Satellite System (TSS).
- STS-47—the Space Shuttle Endeavour will carry Spacelab-J, a combined NASA/NASDA Spacelab mission.
- The Mars Observer will be launched on a Titan III; this launch will feature the first use of the commercial upper stage, called the Transfer Orbit Stage, built by the Orbital Sciences Corp.





UPCOMING EVENTS

WORLD SPACE CONGRESS 1992
IAF · COSPAR

28
AUGUST

World Space Congress, the 43rd Congress of the International Astronautical Federation, in Washington, D. C., through September 9.

IN OUR NEXT ISSUE

International Space Year—Shaping a global space program.

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