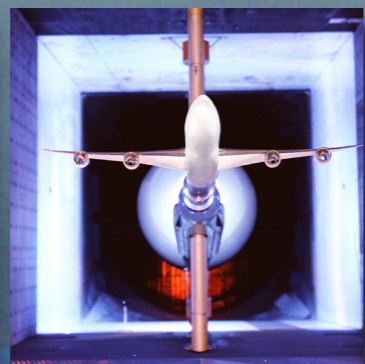
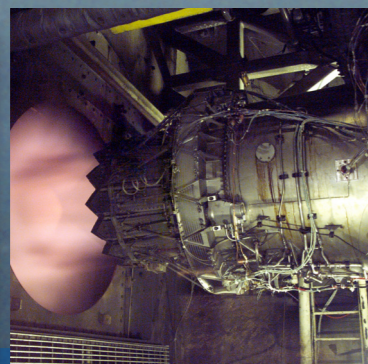




**Beyond the Speed of Sound**



# **Beyond the Speed of Sound**



Arnold Engineering Development Center's contributions to  
America's Air and Space Superiority



# **Beyond the Speed of Sound**



*“The scientists who work here will explore what lies on the other side of the speed of sound. This is part of our effort to make our air power the best in the world — and to keep it the best in the world. This applies to the planes of the Air Force, the Navy and our Marines. It applies to our guided missiles and all the future developments that science may bring.”*

President Harry S Truman  
AEDC Dedication Speech  
June 25, 1951



# Acknowledgements

This book is a credit to all the men and women who work and have worked at the U. S. Air Force’s Arnold Engineering Development Center (AEDC) making significant contributions to the advancement of aerospace technology. These contributions have made General of the Air Force Henry H. “Hap” Arnold’s vision of “An Air Force Second to None” a reality.

Without an institution like AEDC, many of the advances in flight technology that have made America an aerospace power might not have come to fruition.

The vision and direction to create this book came from former AEDC Commander Retired Brig. Gen. David Stringer and Aerospace Testing Alliance (ATA) General Manager Dr. David Elrod.

The staff of the ATA Public Affairs Office compiled publicly released information — produced by several generations of AEDC writers and photographers— that spanned more than half a century to research, write and design this publication.

Credit for production of this book goes to the entire ATA Public Affairs staff with support from Information International Associates, Inc., (IIA) Graphics and Technical Publications personnel. Key contributors include:

- Claude Morse — Executive editor
- Darbie Sizemore — Editor, lead writer
- Stephanie Warren — Researcher
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- Rick Goodfriend, David Housch, the AEDC Photo Lab — Photography

Many other people also provided insight and contributions over a two-year period as this product moved from concept to reality. To each of them, we send our thanks.

Special thanks to AEDC Fellows Dick Austin, Dean Herron and Robert E. Smith, along with Dr. Ed Kraft and Dr. David Elrod, for their reviews and inputs for this book.



# Foreword

This book is a high-level view of the history of the Air Force's Arnold Engineering Development Center (AEDC) at Arnold Air Force Base (AFB), Tennessee, and contains reference chapters on many of the key aerospace systems that have been tested in AEDC's ground flight simulation facilities.

It is by no means a complete list of all the aircraft and weapons systems, NASA spacecraft and commercial aviation products that have made use of AEDC's unique test facilities throughout their development, improvement and sustainment life cycles. Rather, it is a sampling with overviews of the types of testing done. The material is based entirely on cleared news releases (*References, page 207*), which means in some cases there may have been actual test work that is not covered in these pages. To completely cover all the programs the center has supported would require several volumes.

AEDC works closely in cooperation with Department of Defense (DoD) program offices, NASA programs, aerospace industry and other ground and flight and armament test centers to create an integrated test and evaluation program. This begins with test concepts aimed at helping developers understand what AEDC can contribute to validate designs and reduce risk by building the right test plan for their program at AEDC. Many systems have benefited from the center's expertise and have tested in AEDC's facilities from "cradle-to-grave."

This book has been divided into chapters or profiles based upon the systems tested at AEDC. Each profile is a high-level summary of the testing or analysis work conducted on the system while in the center's facilities. There are some gaps in coverage on some programs because of a lack of publically-cleared information.

While a few systems have undergone only one type of testing at the center — propulsion, aerodynamic, store separation or space simulation — most systems have undergone a battery of testing in multiple test facilities.

The initial work done at the center normally takes place before the system undergoes any flight testing at either an Air Force, Navy or commercial flight test facility.

For more than half a century, the dedicated men and women at AEDC have made significant contributions to the development of almost every high-performance military flight system, space launch and weapons program, as well as NASA manned space systems and many commercial aircraft.

This book is dedicated to the people who have worked tirelessly to fulfill the vision of General of the Air Force Henry "Hap" Arnold, that is, "An Air Force Second to None!"

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# **Beyond the Speed of Sound**

# What is AEDC?

The Air Engineering Development Center was authorized by an act of the 81st Congress, Public Law 415, approved Oct. 27, 1949. (*Appendix 2*)

On March 7, 1950, the Air Engineering Development Center was redesignated the Arnold Engineering Development Center (AEDC) effective Feb. 10, 1950, per General Order #23, signed by then-Chief of Staff of the Air Force, General Hoyt S. Vandenberg.

The center is a part of a master unitary wind tunnel plan that is designated to provide the testing “tools” required to assure the United States continued air and space supremacy.

The necessity for an aeronautical test center of this type was recognized by a number of different agencies of the government, as well as by expert technical groups from the industrial-scientific world. The creation of these research and testing facilities has enabled the U.S. to stay abreast of developments in this fast-moving field.

AEDC is the most advanced and largest complex of flight simulation test facilities in the world with a replacement value of more than \$7.8 billion.

At one time or another, the center has operated 58 aerodynamic and propulsion wind tunnels, rocket and turbine engine test cells, space environmental chambers, arc heaters, ballistic ranges and other specialized units. Twenty-seven of the center’s test units have capabilities unmatched elsewhere in the United States; 14 are unique in the world.

Facilities can simulate flight conditions from sea level to 300 miles altitude and from subsonic velocities to Mach 14.

AEDC’s mission is to:

- Test and evaluate aircraft, missile and space systems and subsystems at the flight conditions they will experience during a mission to help customers develop and qualify the systems for flight, improve system designs and establish performance before production. It also helps users troubleshoot problems with operational systems.

- Conduct a research and technology program to develop advanced testing techniques and instrumentation and to support the design of new test facilities. Continuous improvement helps satisfy testing needs and keeps pace with rapidly advancing aircraft, missile and space system requirements.
- Maintain and modernize the center’s existing test facilities.

AEDC is an important national resource and has contributed to the development of practically every one of the nation’s top priority aerospace programs, including better spacelift, aircraft, missiles and satellites. Many of these programs are highlighted in the following sections.

AEDC is an Air Force Materiel Command (AFMC) organization managed by the Air Force but operated largely by a contractor work force. While AEDC’s primary location is in Tennessee, it also operates two geographically separated facilities – the Hypervelocity Wind Tunnel 9 in Maryland, and the National Full-Scale Aerodynamics Complex (NFAC), in California.

AEDC’s economic impact to the local area for fiscal year 2008 exceeded \$728 million. The total economic impact includes the center’s payroll, secondary jobs created locally through the spending of that payroll, and other expenditures for supplies, utilities, fuel and services and the spin-off impact of those purchases.



# The History of AEDC

Amid the ashes of World War II, American scientists surveying German technology were disturbed to find a sophisticated network of flight simulation test facilities. It was a wake-up call for the future – a realization that the United States was years behind the Germans in the process of developing aerospace technology.

Fortunately, the Germans had developed these technologies too late to turn the tide of the war.

However, the discovery of these facilities confirmed the suspicions of General of the Air Force Henry H. “Hap” Arnold, commanding general of the Army Air Forces during World War II. Arnold had been preoccupied with the role of technology, research and development of air power even before the war.

## General Arnold’s Vision

When Hap Arnold visited England in the spring of 1941, he saw a British plane flying without a propeller. “Regardless of what anybody says, I want this for the U.S.,” he said.

But American production lines were geared up trying to maintain the flow of military hardware to the Allies, and they had no quick way of restructuring their assembly lines for something as drastic as a new type of engine. Besides, Arnold didn’t want to interrupt assembly of material he would need in the future. However, this wasn’t enough to stop him when he had a hot project on his mind; he simply brought new people into the business.

He talked General Electric into manufacturing the British Whittle engine and began looking for someone to build the airframe. Since Bell Aircraft had no major contracts in the works, he convinced Larry Bell to take on the job.

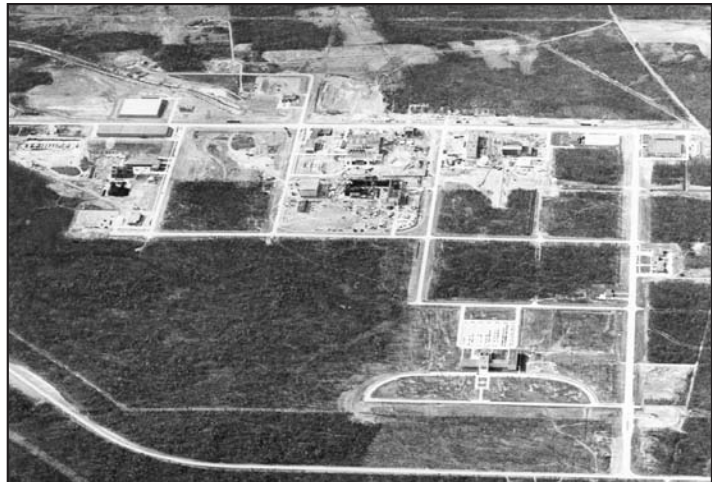
Around Oct. 1, 1942, the Bell XP-59A Airacomet made its first flight at Muroc Dry Lake (the current site of Edwards Air Force Base [AFB], California). The Army Air Corps had entered the jet age through Arnold’s initiative.

Arnold was quick to grasp any new development, but he also realized that the production of new hardware required the establishment of research and development organizations, as well as new and better testing facilities. The most revealing account of Arnold’s foresight is related by Dr. Theodore von Kármán in his autobiography, *“The Wind and Beyond.”* Arnold had appointed von Kármán to be his special adviser at Wright Field, Ohio, in 1940.

According to von Kármán, Arnold met him in a staff car at New York’s LaGuardia Airport in 1944 to discuss the future. Even at that time, the general knew the war was won, and his mind was already racing ahead in an attempt to determine future defense needs.

“General Arnold wasted no time in coming to the point,” von Kármán wrote. ‘We have won this war and I am no longer interested in it,’ he said. ‘I do not think we should spend time debating whether we obtained the victory by sheer power or by some qualitative superiority. Only one thing should concern us. What is the future of air power and aerial warfare? What is the bearing of the new inventions such as jet propulsion, rockets, radar and the other electronic devices?’

“I listened with fascination. I had always admired Arnold’s great vision, but I think then that I was more impressed than ever. This was September 1944. The war



Top, Arnold Engineering Development Center (AEDC) as it appeared during its construction in the 1950s. Below, AEDC in 2008.

was not over; in fact, the Germans were to launch the Battle of the Bulge in December. Yet, Arnold was already casting his sights far beyond the war and realizing, as he always had, that the technical genius which could help find answers for him was not cooped up in military or civilian bureaucracy, but was to be found in universities and in the people at large.

“What do you want me to do, General?’ I said.

“I want you to come to the Pentagon and gather a group of scientists who will work out a blueprint for air research for the next 20, 30, perhaps 50 years.”

### The Scientific Advisory Group

Arnold asked von Kármán to form an advisory group, responsible only to the Air Corps Chief, to provide recommendations on the direction aviation research should take. Arnold formalized this request in a letter to the group dated Nov. 7, 1944. In the letter, he specified four major questions the group was to answer:

1. What assistance should we give or ask from our educational and commercial scientific organizations during peacetime?
2. Is the time approaching when all our scientists and their organizations must give a small portion of their time and resources to assist in avoiding future national peril and winning the next war?
3. What are the best methods of instituting the pilot



On April 28, 1948, the Research and Development Board Committee approved the Camp Forrest site for AEDC and recommended the prompt initiation of construction.

production of required non-revenue equipment of no commercial value developed exclusively for the post-war period?

4. What proportion of available money should be allocated to research and development?

Von Kármán sent a task force from his newly formed Scientific Advisory Group (SAG) to take a closer look at German test facilities. In May 1945, they followed their analyses with a trip to Germany, again at Arnold’s insistence, to find out what testing and research facilities had been in operation.



Near the end of a rainy April in 1950, a photo was taken of the center’s first commander, Maj. Gen. Frank Carroll, at the base stake for the construction grid. During a center tour some 15 years later, AEDC photographer Phil Tarver asked Gen. Carroll to strike the same pose – note the cigar – at the same location.

## The History of AEDC

At Braunschweig, Munich, Goettingen, Kochel, Oetzal and other test centers in Germany they found facilities, rockets, aircraft and jet engines – all more advanced than what the Allies had even imagined. Dr. Frank Wattendorf was one of the American scientists who made the trek to Germany. He was responsible for surveying German wind tunnels and engine test facilities.

As one of von Kármán's associates during the survey of captured German test and research facilities, Wattendorf knew first hand the sad state of aeronautical research in the U.S. The Germans had far outclassed all of the Allied nations in ground testing, but the capture of these testing facilities would give the U.S. a big boost. In fact, it was just the solution Wattendorf needed to a problem presented to him by Brig. Gen. Franklin O. Carroll, commander of Wright Field's engineering division.

### A New Challenge

Carroll wasn't new to research and testing facilities. He graduated from the Massachusetts Institute of Technology (MIT) in 1921 – the first Air Service officer to be trained in aeronautical engineering. He had also commanded the engineering division at Wright Field for six years. In that capacity, he tried to persuade von Kármán to leave Washington, D.C., and work at Wright Field instead. Carroll was the kind of “doer” that Arnold liked to have around.

But he had one big headache at Wright Field – the limited space and available power in the Dayton area. New test facilities for testing jet engines would require more of both – more than he had available without drastically reshaping existing facilities.

When Wattendorf reported to Carroll as a research adviser, he inherited the General's headache – how to fit new facilities into the existing space and power limitations. The trip to Europe with von Kármán opened new possibilities.

### The Trans-Atlantic Memo

With the survey of German facilities completed,



1945



1950



1950

## The 1940s

**November 1944** – General Arnold directs formation of the Scientific Advisory Group (SAG).

**June 1945** – *Trans-Atlantic Memo* proposes the Air Engineering Development Center.

**December 1945** – Dr. Theodore von Kármán's report *Toward New Horizons* lays the foundation for an Air Force research and development program.

**March 1946** – Sverdrup & Parcel awarded contract to study possible sites for the Air Engineering Development Center.

**September 1947** – The United States Air Force becomes a separate military service.

**April 28, 1948** – The former Army training area Camp Forrest is named as the site for the Air Engineering Development Center.

**1949** – Congress authorizes \$100 million for the construction of the Air Engineering Development Center.

## The 1950s

**March 3, 1950** – The Secretary of Defense approves construction of the new facility.

**June 2, 1950** – The Army Corps of Engineers begins construction on a perimeter fence and access road.

**June 23, 1950** – Work begins on a dam on the Elk River to create a reservoir to provide cooling water for testing facilities.

**June 29, 1950** – The Arnold Research Organization (ARO) is awarded a contract from the Air Force to operate AEDC for 15 months.



Left, President Harry S Truman dedicated AEDC June 25, 1951. Right, local residents braved Tennessee’s June heat to attend the dedication of AEDC.



Wattendorf went to Paris to write up his findings. While there, he received word that his father had died, and he left on emergency leave aboard a C-54. It would be a long flight, which gave him a perfect opportunity to summarize his findings.

Wattendorf’s report of June 19, 1945, became known as the *Trans-Atlantic Memo* and was to become the baseline for establishing a “new Air Forces development center.”

The memo, given to Carroll through Col. Paul H. Kemmer, became the basis of Carroll’s presentation to Arnold’s Air Staff.

In his presentation, Carroll advised the Air Staff of the advancements in ground testing that the Germans had made and outlined the deficiencies in America’s wind tunnels.

He noted that “no facilities exist [in the U.S.] for the testing of turbojet compressors.” Carroll also listed what he felt were the necessary facilities for U.S. research and development, suggesting that the Air Technical Service Command be charged with making a preliminary study “for the establishment of a new Army Air Force’s (AAF) Applied Research and Development Center for Fluid Dynamics.”

Maj. Gen. E. M. Powers, assistant chief of staff, materiel and services, gave Carroll the green light to proceed on July 31, 1945.

On Oct. 5, Kemmer, Carroll’s deputy, formed a committee to do the study. The Kemmer Committee’s initial report was completed on Dec. 18 for submittal to Arnold, five days before *Toward New Horizons* was published.

Both reports recommended using captured German test facilities in a new installation located near large sources of water and electric power. They anticipated power requirements at more than one million horsepower – too great to be handled at Wright Field. Using the German equipment would save almost eight years in facility design and construction. The Kemmer Committee Report

also asked for \$300 million for purchase of the site and construction of housing, roads, utilities and the initial portion of the facility.

The report, “Proposed Air Engineering Development Center,” was presented to the Air Staff Jan. 24, 1946. On March 21, Brig. Gen. H. I. Hodes, assistant chief of the War Department General Staff, authorized further planning on the proposed center, and Sverdrup & Parcel Inc. (S&P), a St. Louis engineering firm, was awarded a \$1.5 million Army Air Forces contract to conduct the survey.

### Site Selection Begins

S&P recommended, in order of preference: Moses Lake, Washington, Grand Wash Cliffs, Arizona, and the Tennessee Valley as possible sites for the new center. All three were considered acceptable because of power availability, low population density and room for growth.

Moses Lake was the first choice because the Air Force was closing a base there, and buildings and a runway were already in place. But the Air Force Chief of Staff didn’t like the Moses Lake site because he felt it was too vulnerable to attack. Air Force Secretary Stuart Symington thereupon established a committee to look at the other choices.

A water dispute between Arizona and California knocked the Grand Wash Cliffs area out of contention, leaving only the Tennessee Valley to be considered. Huntsville, Alabama, emerged as the preferred site. The Tennessee River would provide ample water, and the Army was deactivating the Redstone Arsenal, which could be used to save time in constructing housing and offices. But when the Air Force started showing interest in Redstone, the Army quickly began to have second thoughts about closing it down.

It was then that Senator Kenneth McKellar of Tennessee made his big pitch: the state of Tennessee would donate Camp Forrest to the Air Force as the site for the Air Engineering Development Center. Not only

## The History of AEDC

that, but he could also help push legislation through Congress. The Air Force couldn't resist. On April 28, 1948, the former Army training camp was named as the site for the Air Force's new Air Engineering Development Center.



1951

The Unitary Wind Tunnel and Air Engineering Development Act of 1949 set aside \$100 million for construction of the new facility. The Secretary of Defense approved construction of AEDC on March 3, 1950, and three weeks later the Air Force awarded its first construction contract: cranes for the Engine Test Facility (ETF). The Army Corps of Engineers, which established a district office in Tullahoma on Nov. 14, 1949, awarded their first construction contract for a perimeter fence and an access road. This work began on June 2, 1950. Three weeks later the Corps awarded a contract to dam the Elk River for a reservoir to provide cooling water for the facilities.

Symington directed on March 29, 1950, that AEDC would be operated by a corporation under contract to the Air Force. Several meetings in early April between Air Force personnel and S&P established the Arnold Research Organization (ARO), Inc., a Tennessee corporation, for managing and operating AEDC on a cost-plus-fixed-fee contract. On June 29, the contract was signed in the amount of \$694,174.50 to cover the first 15 months of operation.

Part of the government's rationale was to maintain a stable work force that would accumulate a volume of experience with the test facilities that were to be built. That idea would make the center a model of outsourcing for the Department of Defense (DoD) by the 1990s.

### AEDC's Dedication

On June 25, 1951, a year after General Arnold's death, President Harry S Truman dedicated the Air Engineering Development Center in Arnold's memory, naming it the Arnold Engineering Development Center.

"I am happy to dedicate this center to his memory and to name it the 'Arnold Engineering Development Center,'" the President said. "The scientists who work here will explore what lies on the other side of the speed of sound. This is part of our



1959

**June 25, 1951** – President Harry S Truman dedicates the facility in honor of five-star General of the Air Force Henry "Hap" Arnold, naming it the Arnold Engineering Development Center.

**Oct. 21, 1952** – PeeWee, a one-foot wind tunnel built to identify problems in the 16-foot tunnels, goes into operation at AEDC.

**1953** – Construction on the Engine Test Facility (ETF) is completed.

**Sept. 9, 1953** – The Falcon guided missile is placed in the test section of tunnel E-1 and is tested at nearly five times the speed of sound.

**1954** – The first engine, a J47 turbojet for the B-47 bomber, is tested at a simulated altitude of 30,000 feet.



1954

**April 1954** – The first issue of *High Mach*, the center's employee newspaper, is published.

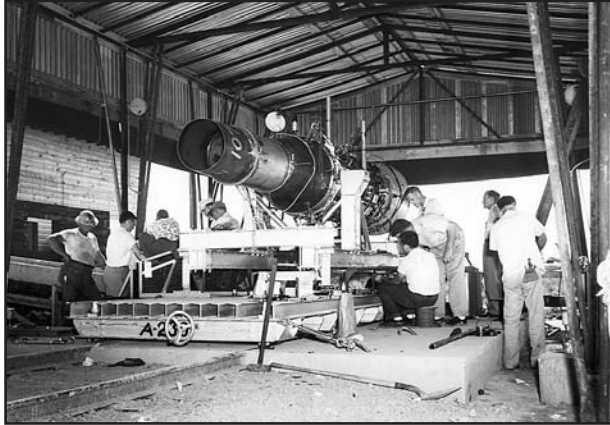
**August 1954** – The Air Force executes another one-year contract, with a four-year option, with ARO.

**March 27, 1957** – Escape velocity, the speed needed to leave Earth's gravity, is reached in the Gas Dynamics Facility's Hotshot 2 tunnel.

**November 1957** – A jet engine is tested in the new Propulsion Wind Tunnel (PWT), validating the larger transonic wind tunnel design.

**July 1959** – The supersonic circuit of the PWT facility is completed.

**Oct. 30, 1959** – A facility designed for testing aerospace designs at high speeds is dedicated to Dr. Theodore von Kármán as the von Kármán Gas Dynamics facility.



The first jet engine test at AEDC's Engine Test Facility took place in 1953. The test required design and construction of a thrust stand for the J47 turbojet engine used in calibrating the center's T-1 high-altitude test cell.



A cornerstone ceremony was held in the Tullahoma National Guard Armory in honor of the University of Tennessee Space Institute (UTSI). Various photographs and documents concerning the institute and its sponsors were sealed in a copper box that was placed beneath the cornerstone of the Gov. Frank G. Clement building on campus.



The enormous size of the supersonic circuit compressor of the PWT facility is illustrated by the comparison of workmen standing below the 18-stage compressor. The supersonic circuit is designed to operate at speeds between Mach 1.5 and 4.5 with altitude simulation capability up to 200,000 feet. The compressor – 18 stages in all – is made up of four barrels, three of four stages each, and one of six stages. They can be operated as a unit or one at a time depending on the test conditions. Steel boxes on the walls contain fiberglass pillows for insulation to retain heat when temperature is a test condition.

effort to make our air power the best in the world and to keep it the best in the world.”

### The First Facilities

The remainder of the 1950s saw the development of three major test facilities that remain active today – the ETF, the von Kármán Gas Dynamics Facility (VKF) and the Propulsion Wind Tunnel (PWT) Facility.

Following Wattendorf's recommendations from six years earlier, the first jet engine test equipment installed at the center was acquired from the Bavarian Motor Works (BMW) in Munich, Germany. It took 58 railroad cars and

two barges plus another 450 tons by truck to move the equipment.

After refurbishment, this equipment became the cornerstone for the ETF, which was completed in 1953. By May 1954, the facility was put to work, testing the General Electric (GE) J47 engine for the B-47 bomber.

A flight dynamics facility for testing aerospace designs at high speeds was built and then dedicated to von Kármán in 1959. Operations began with a prototype test cell called E-1, which was used to test the Falcon guided missile.

Construction was completed on the PWT facility at the end of the 1950s. PWT's huge wind tunnels have become hallmarks of the center and are perhaps the most heavily used facilities on base.

### Forming Academic Alliances

Before AEDC reached full operability, efforts were under way to affiliate the center with universities. The Industry and Educational Advisory Board, in meetings on May 11-12, 1951, considered drafts of a proposed contract with the University of Tennessee (UT) and recommended that a program be developed to provide qualified AEDC personnel university-level courses leading to advanced degrees in physical and engineering sciences and “instruction in such other fields as circumstances may justify.”

On June 19, 1951, the Air Force awarded a letter contract to UT to study the board's recommendations. Under the direction of Dr. Wiley Thomas, UT completed the study and submitted a final report on Dec. 1, 1952. Included in this report was a recommendation by the Graduate Study Committee that a program of residence graduate courses



## The History of AEDC

and degrees for AEDC employees be established. The study also recommended lecture and symposia programs to put center personnel in contact with leaders of aviation, industry and science. Most significantly, the UT study recommended that an Institute of Flight Science be established at AEDC. The institute should “engage the human and institutional resources of the entire free world and should foster especially close ties with neighboring southern educational institutions.” The report noted that such an institute would be a “very natural extension of the proposed graduate degree program” and projected that it “might well develop in an organic way from these programs.”

The proposal rested on the expectation that activities of the institute would become a valuable factor in attracting and retaining the scientific personnel required for the full development of AEDC.

The UT program to award graduate degrees to engineers on staff of the Air Force and ARO at AEDC was approved in Washington, D.C., on May 3, 1956. Twenty-two master’s degrees would be earned through the program over the next eight years at the University of Tennessee Space Institute (UTSI).

### The “Race to Space”

As the space race heated up, so did AEDC’s workload. PWT was used to investigate configurations for the Mercury space capsule, which sent Alan Shepherd and John Glenn into space. The center was a key player in supporting Project Gemini, and the center played a multi-faceted role in supporting the Apollo Program, which put man on the moon. Apollo tests included aerodynamic assessments of the Apollo capsule and tests of Saturn V rocket upper-stage engines.

Some new test facilities came online during the 1960s that helped turn numerous aerospace system ideas into reality.

The J-4 Large Rocket Engine Test Facility was dedicated in 1964. PWT got an addition in 1968 when the 4-foot transonic tunnel (4T) came on line. 4T was, and still is, used largely to test store separation.



1960



1961



1965

## The 1960s

**1960** – Sverdrup and Parcel marks the 10th anniversary of the start of construction on the AEDC project.

**1960** – ARO photographer Phil Tarver shoots the iconic wind tunnel photo.

**July 1960** – The Air Force and ARO agree to a new contract for fiscal year 1961.

**Jan. 13, 1961** – The supersonic circuit of PWT is accepted by the Air Force.

**June 23, 1961** – Air Force Secretary Eugene Zuckert comes to AEDC to break ground for J-4, the world’s largest rocket altitude cell.

**Jan. 23, 1963** – Congress votes \$944,000 for the construction of the J-5 rocket test facility.

**Dec. 11, 1963** – The Air Force accepts both the J-4 and J-5 rocket test cells.

**Dec. 19, 1963** – The first rocket engine – a Skybolt – is fired in J-5.

**1964** – The J-4 Large Rocket Engine Test Facility is dedicated.

**1965** – The University of Tennessee Space Institute (UTSI) is established.

**1968** – A 4-foot transonic wind tunnel (4T) is added to the PWT facility.

**May 9, 1969** – The McDonnell Douglas F-15 begins testing in the 16-foot supersonic wind tunnel.

Store separation testing evaluates how a weapon, fuel tank or other object will separate from an aircraft in flight at different air speeds and angles of flight.

With several test facilities running at full bore, the pace of testing increased exponentially. Among the systems tested during the decade were the F-105 Thunderchief, the C-141 Starlifter and C-5 Galaxy cargo planes, the E-3 Sentry, Airborne Warning and Control System (AWACS), the TF39 engine for the C-5, and the upper-stage rocket motors for the Minuteman Intercontinental Ballistic Missile (ICBM).

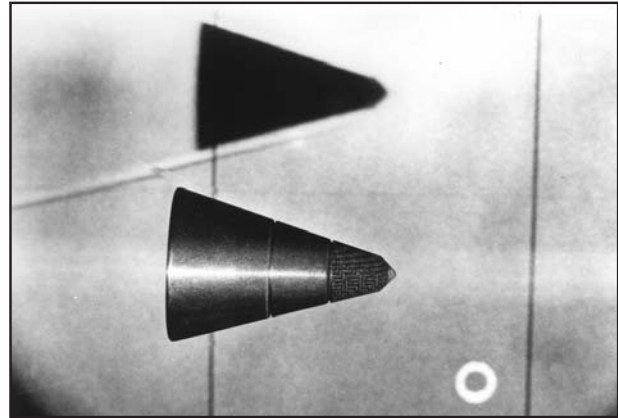
There came a natural turndown in the furious pace of aerospace activities after the moon landing and the end of the Vietnam War. But despite the turndown and a corresponding reduction by the government in funding for AEDC and in the number of center employees, the pace of testing held steady as nearly 3,000 test projects were completed in the decade. The list of systems tested during the decade reads like a who's who of aerospace. Included on that list are the Space Transportation System, which would later be called the space shuttle, the F-15 Eagle, F-16 Fighting Falcon, B-1 Lancer bomber, A-10 Thunderbolt II, Pratt & Whitney F100 engine, MX missile, Sidewinder missile, Navy Tomahawk Cruise Missile, Air Force Air-Launched Cruise Missile (ALCM) and the Global Positioning System (GPS).

AEDC developed Laser-Illuminated Photography during the 1970s to better study projectiles that would be traveling up to 20,000 mph in the center's ballistic ranges. This technique provided a photographic exposure equivalent to 20 billionths of a second.

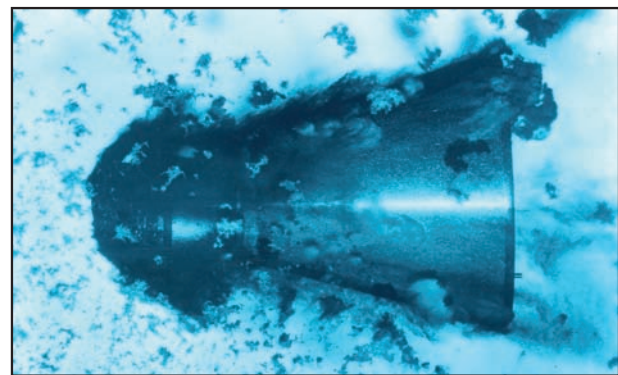
Also during the 1970s, NASA's emphasis shifted from deep-space exploration to near-Earth space operations and development of Skylab and the space shuttle. During that time AEDC evaluated various model configurations for the space shuttle program, obtaining data on heat transfer, as well as aerodynamic forces and pressures. These tests helped to determine the appropriate construction materials and establish baseline flight models for the ascent portion of the mission. The tests also included aerodynamic predictions for the two strap-on, solid-propellant boosters that separated from the shuttle after burnout.

AEDC has supported NASA throughout space shuttle operations, as required, to address potential operational scenarios and anomalies. During this time, wind tunnel tests assessed the effect of a space shuttle main engine failure during the initial stages of ascent.

A heritage of environmental stewardship and uniqueness was made official in 1976 when the Department of Interior registered AEDC as a unique natural area. The honor recognized AEDC's superior management of fish and wildlife resources, conservation practices and environmental achievement. And, in a decade when the nation turned energy conscious, AEDC helped explore



Laser-illuminated photography was developed at AEDC to study ablative effects on a 12,000 mph free-flight projectile in the center's 1,000-foot hypervelocity ballistic range. The technique provided a photographic exposure equivalent to 20 billionths of a second. This photo was taken in 1970.



Models carrying candidate materials for reentry vehicles can be launched free-flight at speeds up to 30,000 feet per second in hyperballistic ranges to determine the effects of reentry environment such as snow and other abrasive elements in the atmosphere on the materials.

alternative energy sources.

A 750-ton magnet was used as part of a magneto-hydrodynamics (MHD) research demonstration at the center, under sponsorship of the Department of Energy. The demonstration assessed the effectiveness of using a large MHD generator to boost the efficiency of coal in producing electricity. AEDC later transferred the project to UTSI.

The decade also marked the beginning of the planning stages for the addition of the world's largest jet engine testing facility – the Aeropropulsion Systems Test Facility (ASTF) – to the center's collection of aerospace flight simulation test facilities.

### Contractor Changes

In 1981, for the first time in the center's history, operations and support work was divided among multiple contractors. The workload was split into three contracts: support, propulsion testing and aerodynamics testing.

## The History of AEDC

Pan Am World Services became the support contractor; Sverdrup Technology Inc. took over propulsion testing, and Calspan Corporation assumed responsibility for aerodynamics and space testing.

In 1985, Schneider Services International replaced Pan Am as the support contractor.

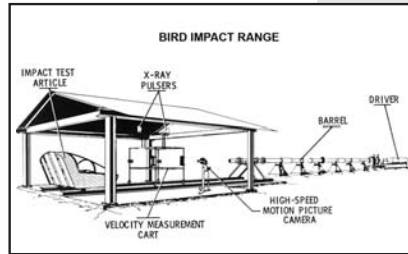
### A New War

The conflict in the Persian Gulf at the beginning of the 1990s became a defining event in late 20th century America. It also showed the world what AEDC had been doing in the 1980s. As people around the world watched from their living rooms, they saw the United States achieve an overwhelming victory in Desert Storm, and what they saw was the end product of what AEDC's people had been working on throughout the decade.

From the Patriot Air Defense Missile to the F-117A Nighthawk stealth fighter, AEDC's people worked on every high-performance aerospace system deployed to the Persian Gulf. It was the first time that technology showed up so dramatically in a real-world conflict, and it was a testament to the test and development work that Arnold, von Kármán and Wattendorf had planned for AEDC.

The 1990s was a decade of change at AEDC. From opening its doors to commercial customers to "reengineering," the center's people explored new ways of doing business. Early in the decade, the center signed formal, long-term working alliances with a number of commercial aerospace organizations – Boeing, GE, Lockheed, McDonnell Douglas and Pratt & Whitney (P&W) – in hopes of steadying workload and offsetting dwindling defense budgets.

Late in the decade, AEDC signed a 10-year contract with Space Systems Loral to test satellites and renovate the center's Mark I Space Environmental Chamber. That led to companies like Pratt & Whitney, Boeing and Loral bringing strictly commercial projects to AEDC. AEDC leaders began to emphasize strategic



## The 1970s

April 1970 – ARO celebrates its 20 year anniversary.

1972 – A design contract is awarded for construction of the new Aeropropulsion Systems Test Facility (ASTF).

1972 – A launcher to determine the effect of impacts of birds on high-speed aircraft is developed.

1976 – The Department of Interior registers AEDC as a unique, natural area.

1977 – ARO is awarded a three year contract for operations at AEDC.



1984

## The 1980s

1981 – For the first time, multiple contractors begin performing work at AEDC.

1982 – Use of Computation Fluid Dynamics (CFD) begins.

Oct. 2, 1984 – Construction is completed on ASTF, the world's largest jet engine test facility.

Nov. 23, 1985 – An explosion during a test destroys the J-5 Rocket Test Facility. The facility is rebuilt a year later, ahead of schedule.



1993

## The 1990s

1992-3 – AEDC formalizes alliances with a number of commercial aerospace organizations.

1993 – The first large commercial engine test takes place.

1994 – The J-6 Large Rocket Test Facility is completed.

management, meeting in focus groups to consider the long-term health of the center and to formulate ways to make the future brighter. An outgrowth was the process termed “reengineering” that sought to streamline operations and standardize maintenance activities.

The 1990s also saw AEDC break new ground on the computational front. Computational Fluid Dynamics (CFD), using computers to simulate flight, saw an ever-increasing role in the scope of many major test programs. Using CFD and traditional ground testing together helped to hold down costs and provide data needed by test customers.

In 1998, the center was designated one of the DoD’s High-Performance Computing Centers, making funding available to augment the center’s supercomputing capability. This designation made AEDC the ninth largest high-performance computing center in the DoD.

The Navy docked at AEDC when its engine test facilities at Trenton, New Jersey, were transferred to AEDC as part of DoD consolidation under the 1995 Base Realignment and Closure Act (BRAC). The move added four engine test facilities (SL-2, SL-3, T-11 and T-12) and about 10 Navy people to AEDC.

Later in the decade, Oct. 1, 1997, AEDC assumed management of the former Naval Surface Warfare Center Hypervelocity Wind Tunnel 9 at White Oak in Silver Spring, Maryland, also as a part of BRAC.

Facilities that came online during the 1990s paved the way for new and continued testing on advanced systems. These facilities were the new Large Rocket Motor Test Facility J-6 – the world’s largest altitude solid rocket motor test facility – and Decade, a nuclear weapons effects facility.

Among facilities that saw significant modernization were the J-4 Liquid Rocket Engine Test Facility, the Aerodynamic and Propulsion Test Unit (APTU), the Mark I Space Environmental Chamber and the ETF. The PWT complex also saw a major \$80 million sustainment program begin.

A number of major aerospace programs began testing at AEDC in the 1990s. Those included the F-22A Raptor and both Joint Strike Fighter (JSF) competitive prototypes, which had been undergoing test flights at Edwards AFB. The P&W F119 engine, the Raptor’s power plant, met Initial Service Release (ISR) qualifications in 2000. The JSF variant of the F119, which became the F135, underwent further testing. The Navy’s newest strike fighter/attack aircraft, the F/A-18 E/F Super Hornet, continued to undergo testing in the center’s wind tunnels. Also completed in 2000 were store separation tests on the Air Force’s B-2 Spirit bomber.

In the commercial arena, P&W continued testing on its 4000 series engines for the Boeing 777. Boeing tested aerodynamic models of the 747, 767 and 777 as well as



**A British A300-B2 Airbus model undergoes wind tunnel testing and evaluation in 1996.**

the RL-10 rocket engine. Other millennium milestones for the center included adding cold X-ray test capabilities to Decade, conducting the first Electric Propulsion Thruster firing in an upgraded 12V Space Chamber and completing the first test in VKF’s 70-foot sphere. A new record was set in G-Range on projectile weight and speed, and a new missile interceptor test capability was developed.

### Contract Consolidation

The center’s outsourced workload was consolidated into two contracts – test and support – in 1995, with Sverdrup Technology Inc., as test support contractor and ACS, a joint venture of Computer Sciences Corp. (CSC), DynCorp and General Physics, as center support contractor. In 2000, the Air Force exercised both prime contractors’ three-year extension options, giving both ACS and Sverdrup three more years at AEDC.

The center also inked agreements with NASA’s Marshall Space Flight Center (MSFC) and the Oak Ridge National Labs and reaffirmed and formalized close educational ties with UTSI, Motlow State Community College, Middle Tennessee State University (MTSU) and Vanderbilt University. Cooperative Research and Development Agreements (CRDA) were signed in 2001 with Micro Craft, a division of Allied Aerospace Industries, Inc., and Engineering Design and Analysis Solutions, Inc.

In the summer of 2003, after an 18-month source selection process, AEDC awarded a single contract valued at up to \$2.7 billion to Aerospace Testing Alliance (ATA) for the operation, maintenance, information management and support of center test facilities beginning Oct. 1, 2003. ATA is a joint venture of Jacobs Sverdrup, CSC and General Physics Corp.

The new contract was a cost-plus-award-fee

## The History of AEDC

performance-based services contract with one-year options that may be exercised by the Air Force through Sept. 30, 2015.

### Looking Toward the Future

As America worked to get back into space following the *Columbia* accident in 2003, AEDC supported several aspects of the space shuttle “return-to-flight” program to flight-qualify the redesign of the bipod fixture that connects the liquid fuel tank to the shuttle.

Arnold employees designed and fabricated full-scale calibration models of the original and redesigned components and a 30-percent scale model of the redesigned area. Tests conducted in 4T, Tunnel A and Tunnel C greatly expanded NASA’s database of localized thermal and pressure measurements in the bipod region and improved their CFD data.

In March 2006, AEDC assumed responsibility to operate the National Full-Scale Aerodynamics Complex (NFAC) located at Moffett Field, California, under a lease from NASA. This facility, with a staff of about 35, has the distinction of being the world’s largest wind tunnel.

### A New Century

In the fall of 2007, AEDC conducted the first ground testing of the GE F101 engine using a 50-50 mix of Fischer-Tropsch (FT) synthetic and JP-8 jet fuels. AEDC took an active role in supporting the Air Force’s evaluation and certification of alternative fuel. The FT process for synthesizing fuel could decrease the nation’s dependence on foreign oil. Furthermore, some tests have shown that FT-blended reduces smoke and particulate emissions.

AEDC is as dedicated to supporting the development and sustainment of America’s defense and commercial aerospace systems in the 21st century as it was in the last half of the 20th century. Thus, General Arnold’s vision that America should always lead in flight technology remains as vibrant as ever.

The AEDC complex has come a long way since Aug. 11, 1950, when 58 freight train cars arrived in Tullahoma loaded with captured equipment used by Nazi Germany to test their first jet engines.

America is an aerospace nation. Air and space systems protect our freedoms, and commercial aircraft and jet engines are one of America’s biggest exports. AEDC plays an integral role in keeping America on the cutting edge of technology. The center is vital to the nation’s defense, playing a key role in the development of nearly every high-performance flight system in use by today’s Air Force, Navy, Army and Marines.



1997

**Oct. 1, 1995** – Sverdrup Technology and Aerospace Center Support (ACS) begin their five-year contract with AEDC.

**1996** – The Decade facility is completed.

**Oct. 1, 1997** – AEDC assumes management of the Hypervelocity Wind Tunnel 9 in Silver Spring, Maryland.

**1998** – AEDC is named one of the DoD’s High-Performance Computing Centers.

## The 2000s

**2000** – Mark I is renovated

**June 25, 2001** – Rededication of the center marks its 50th anniversary

**Oct. 1, 2003** – Aerospace Testing Alliance (ATA), a joint venture between Jacobs Sverdrup, Computer Sciences Corporation and General Physics, begins a 12-year contract as the center’s single contractor.

**2006** – AEDC assumes control of the NFAC, located at NASA’s Ames Research Center, California.



2007

**Jan. 26, 2007** – Arnold AFB receives the 2006 DoD Gen. Thomas D. White Environmental Award for Natural Resources Conservation.

**June 25, 2007** – AEDC commemorates its designation as an American Institute of Aeronautics and Astronautics (AIAA) historic site.

**April 7, 2008** – NFAC tests new helicopter rotor system, marking first military test since facility reactivation.

**Oct. 24, 2008** – Air Force awards \$26.1 million contract to produce the Space Threat Assessment Testbed ground test capability at AEDC.

**Nov. 21, 2008** – AEDC and Pratt & Whitney celebrate 50-year partnership.

**March 6, 2009** – The 100<sup>th</sup> rocket motor is fired in J-6.



## Systems Tested



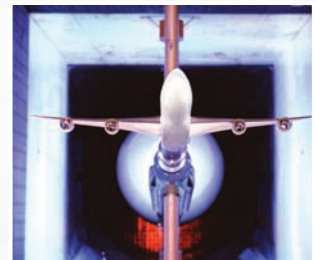
F-22A Raptor



Space Shuttle



Peacekeeper



Boeing 747

# Systems Tested Overview

It is a beautiful day in 2009, when the sharp crack of a sonic boom rattles windows as one of the Air Force's newest fighters – the F-22A Raptor – flies overhead. Below, jet engine technicians prepare to put a Pratt & Whitney F119 engine, the same engine that powers the Raptor, through a strenuous simulated combat flight.

Nearby, technicians attach an Advanced Medium-Range Air-to-Air Missile (AMRAAM) to a F-35 Lightning II Joint Strike Fighter, while technicians work on a F135 engine for the F-35 in another facility.

In a large, hanger-like building, a B-1 Lancer, B-2 Spirit, F-15 Strike Eagle, F-16 Fighting Falcon, a F/A-18 E/F Super Hornet and even a Global Hawk unmanned aerial vehicle have waited for their turn to fly.

On the base's extensive firing ranges, Air Force personnel and units from the 101st Airborne and National Guard train before deploying overseas.

While it seems like a description of a typical Air Force base in 2009, there is nothing typical about this location.

It is the Air Force Materiel Command's (AFMC) AEDC. An Air Force test center with a mission and history as unique as its namesake, it plays a key role in keeping America on the cutting edge of aerospace technology. As air and space systems protect our country, the center is vital to the nation's defense.

The F-22A creating the sonic boom high over Arnold Air Force Base (AFB) is on a supersonic military acceptance flight out of Lockheed Martin's assembly plant in Marietta, Georgia. It never lands at Arnold but flies over the base at more than 40,000 feet. The sonic booms remind the scientists, engineers and technicians on the base what their mission is all about.

AEDC began testing the Pratt & Whitney (P&W) F119 engine in simulated altitude jet engine test cells in 1989 and has been testing these engines ever since to ensure that the engine will be as reliable and robust as technology can make it. A few months after that initial test, early scale models of the YF-22 took flight in AEDC's wind tunnels.

In 1991, the F-22 was selected to be the Air Force's next-generation stealthy air dominance fighter. Years

of testing to refine the Raptor and its jet engines, as well as weapons integration and clean weapons separation in flight, began at Arnold, long before the first production F-22A flew.

As for the aircraft awaiting testing, the B-1, B-2, F-15, F-16, F/A-18 and the Global Hawk in AEDC's model installation building are highly instrumented scale models for wind tunnel testing. They play a critical role in making sure Airmen and Naval Aviators have the best tools possible to support Operation Enduring Freedom and Operation Iraqi Freedom.

These precision models can cost as much as \$3 million each, but they deliver far greater worth to our troops. Before any weapon is carried or released from actual combat aircraft, scale models of the weapons and aircraft are tested in AEDC's wind tunnels to ensure clean weapons separation in flight.

The jet engines being readied for flight are highly instrumented and make their flights in test cells that simulate the altitudes from ground level to near space and at speeds up to several times the speed of sound under a full range of temperature and weather conditions. These tests help manufacturers refine and improve the performance and reliability of the engines.

And it is not just new jet engines that are tested at AEDC. The latest version of the venerable P&W F100 that powers the F-15 and F-16 was tested in Arnold's jet engine test cells before it was installed in the aircraft and flown at Edwards AFB, California.

To really appreciate AEDC's contributions to the nation's defense, it is important to understand how the idea for the center evolved.

When World War II began, standard Air Force fighters had a top speed of approximately 300 miles per hour. At the end of the war, standard fighter aircraft were approaching the speed of sound in dives from high altitudes.

The existing wind tunnels and laboratories of the Air Force, keyed to subsonic flight, were decreasing in value in a science that was pushing into the unknown realm of transonic and supersonic flight. As the speed of military aircraft increased, the forces imposed upon the aircraft severely altered their

normal flight characteristics.

At Wright-Patterson AFB in Dayton, Ohio, five wind tunnels were used in design and development of new aircraft. Only two of these tunnels were capable of transonic and supersonic speeds. There was a need for newer equipment that could keep pace with the accelerated developments of the war years.

Military and civilian scientists became increasingly aware of the shortcomings of the U.S.'s current research and development facilities. Personnel charged with development projects could not adapt the older equipment to new problems brought about by supersonic flight.

As a result, the Wright Field laboratories started planning facilities to cope with their own particular problems. Concrete proposals for new research and development equipment for testing jet engines and components came into being as early as January 1945.

It soon became apparent that the requirements for these new facilities were such that limitations in space, power and utilities would prevent installation of the required facilities at Wright Field.

In the spring of 1945, Gen. Hap Arnold's Scientific Advisory Group wanted to get a first-hand look at the German equipment and survey innovative German developments and plans.

What they found surprised them.

At the Bavarian Motor Works (BMW) plant in Munich, a jet engine test facility was in full operation, with construction already under way to double its capacity, giving it an order of magnitude more capacity than anything in the U.S.

At Oetzal in occupied Austria, an 8-meter diameter sonic wind tunnel was under construction. A novel feature was the use of a hydraulic rather than an electric drive. Water from a lake high above the wind tunnel site was conveyed downward to operate Pelton-wheel turbines, directly powering the wind tunnel drive shafts.

At Kochel, south of Munich, a 1-meter-by-1-meter hypersonic battery of tunnels capable of operation though the Mach 10 range was fully designed, with parts ordered and in the early stages of construction.

That visit to Germany made clear to the U.S. scientists and planners what they needed to do to get the U.S. on track to realize Hap Arnold's vision of "An Air Force Second to None."

Today, every high-performance aircraft flown by the Air Force, Navy and Marines can trace part of its

roots to AEDC.

The technological advances achieved in the last 55 years at the center have helped put man on the moon, established America's air dominance, saved American lives on the battlefield and taken the war on terror, with pinpoint precision, to the terrorist.

Those achievements are highlighted in the next four sections of this book. Divided into four sections – Military Systems, Space Systems, Missile Systems and Commercial Systems – selected systems are featured to show the breadth and depth of the work conducted over the last 55 years by countless dedicated AEDC employees.

This is not an all-inclusive list of every system ever tested at the center. Rather, it is a representative sample. Each section contains an introduction followed by a timeline illustrating when each system was first tested at the center. Also since this book is based entirely on cleared news releases, some test work on some flight systems may not be fully covered here.





# Systems Tested Timeline

This timeline illustrates the "big picture" of systems tested at AEDC. Systems are shown based on when they first came to the center not when testing began and ended. The system names are color-coded – blue for Military and Missile systems; orange for Space Systems; and green for Commercial Systems. While those systems in black text are not covered in the book, they do represent important programs.

## The 1950s



BOMARC



Project Mercury

**BOMARC**  
**B-47 Stratojet**

**SM-65 Atlas**

**T-38 Talon**  
**Sergeant Missile**  
**Snark**  
**Nike**

**Project Mercury**  
**Project Gemini**  
**Discoverer**  
**Vanguard**

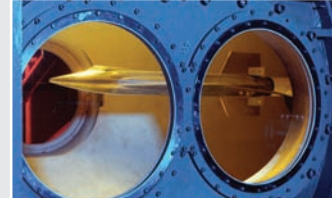
**F-105 Thunderchief**

**B-58 Hustler**

**Polaris SLBM**

**X-15**  
**SM-68 Titan**  
**LGM-30**  
**Minuteman**

**F-5 Freedom Fighter**  
**XB-70 Valkyrie**  
**GAM-78 Quail**



X-15

## The 1960s



Dyna-Soar

**Project Apollo**

**Dyna-Soar**

**C-5 Galaxy**

**Little John**

**E-3A Sentry**  
**Patriot**

**Thor-Delta**

**F-111 Aardvark**

**Voyager**  
**Scout**

**Saturn V**

**Short-Range Attack Missile**

**Viking**



F-111 Aardvark



Short-Range Attack Missile

## The 1970s



Space Transportation System

**Space Transportation System**  
**Trident SLBM**

**Firebee**  
**Poseidon SLBM**  
**YF-17**

**Air-Launched Microfighter**  
**X-24B**

**Pershing**

**Maverick**

**F/A-18 Hornet**  
**Walleye**

**BGM-109**  
**Tomahawk**

**B-1 Lancer**

**F-15 Eagle**  
**Sidewinder**  
**AIM-9**

**F-16 Falcon**  
**F-4 Phantom II**

**A-10 Thunderbolt II**  
**A-7 Corsair**

**X-24C**

**Air-Launched Cruise Missile**  
**F-117 Nighthawk**

**GPS**

**C-141 Starlifter**  
**AMRAAM**

**CF6-50**



Air-Launched Cruise Missile



C-141 Starlifter

## The 1980s



V-22 Osprey

Peacekeeper  
 AV-8B Harrier  
 V-22 Osprey  
 F-22A Raptor

F-14 Tomcat

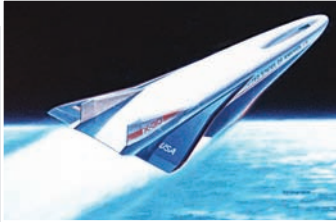
C-17 Globemaster III

X-29  
 YF-23



C-17 Globemaster III

## The 1990s



X-30

X-30

P&W 4084  
 YF-36

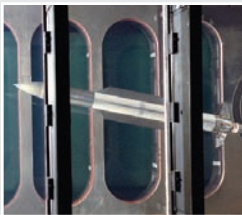
International  
 Space Station

Cassini-Huygens  
 Dornier Alpha Jet  
 F/A-18 Super Hornet



F/A-18 Super Hornet

Boeing 767  
 Navy Standard Missile  
 Trent 800  
 Exoatmospheric Kill  
 Vehicle

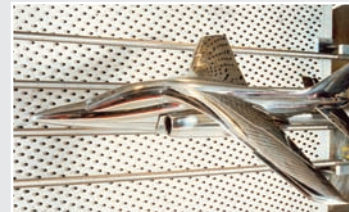


Navy Standard Missile

B-52 Stratofortress  
 KC-135 Stratotanker  
 A300-B2 Airbus  
 Aegis

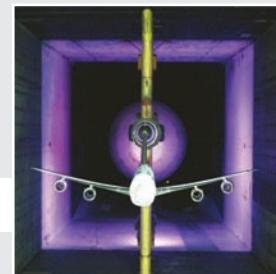
F-35 Lightning II  
 Pathfinder  
 National Missile  
 Defense

B-2 Spirit  
 EELV  
 Boeing 777  
 THAAD  
 RQ-4 Global  
 Hawk



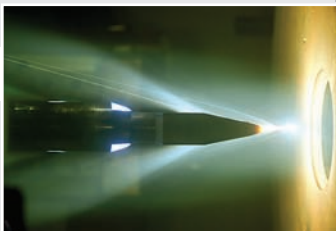
Dornier Alpha Jet

P&W 4090  
 Chandra  
 Standard Missile-3  
 P&W 4098  
 X-33  
 PAC-3



Boeing 747

## The 2000s



X-43 Hyper-X

X-43 Hyper-X

X-37  
 Boeing 747

Airbus A380

EA-18 Growler



EA-18 Growler

P-8A Poseidon  
 Kinetic Energy  
 Interceptors  
 Trent 1000

GOES-M

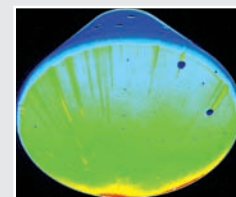
Ground-based  
 Midcourse Defense

Trent 900

GP7200

Crew Exploration Vehicle  
 Mars Science Laboratory

PW6000



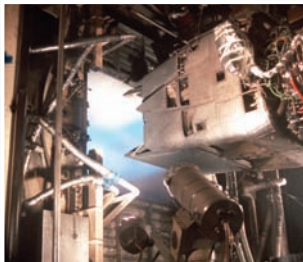
CEV



# Military Flight Systems



F-15 Eagle



F119



AV-8B Harrier



XB-70 Valkyrie

# Military Flight Systems Overview

As early as 1941, Army Air Forces and civilian engineers were experimenting with rocket-powered aircraft with the goal of creating a faster, more maneuverable aircraft for wartime use.

The Nazi Luftwaffe had proven the value of the jet in action over Britain and Europe. In April 1945, 50 German aircraft shot down 10 U.S. bombers over Berlin in the largest loss of aircraft to jets in the war.

But by war's end, the United States was ready to enter the jet age.

Dr. Frank Wattendorf, the writer of the *Trans-Atlantic Memo*, recalled a meeting that, in retrospect, was probably the catalyst to the U.S. entry into the jet age.

*"My first association with General Arnold was in the fall of 1944," Wattendorf said in 1974. "General Arnold called to the Pentagon Dr. von Kármán, the original AAF Scientific Advisory Group and a small group, myself included. We met in his office and found him an extremely impressive and inspiring leader, certainly a man with vision. He said, 'Gentlemen, we are well on our way to winning this war, by brute strength and industrial production, but not by scientific competence and vision.' He said that in looking backwards he realized how little foresight we had used; and that this should never be allowed to happen again."*

*"Therefore, we should be building for the future even before the war was ended. Otherwise there could be a big lapse after the war; and research and development could go back to pre-war conditions. He wanted Dr. von Kármán and his group to look forward at least 20 years in the future, visualizing the long-term potential scientific advances of benefit to the Air Force. This would, in turn, allow him to visualize the best applications to improved weapons systems. Well, we were certainly impressed with him, his candor and his vision."*

In 1945, years of research and testing culminated with the debut of the Army Air Forces' P-80 Shooting Star jet-powered aircraft. The first P-80 fighter group – the 412th – was established at March Field, California, later that year.

The P-80 went on to set a host of speed and distance records, but it wasn't until a Douglas-built

rocket pierced the upper atmosphere in 1946 that Americans began to consider the possibility of going faster and farther.

In the high desert around Muroc, California, test pilots were pushing the envelope and pressing their jet aircraft for more speed, more altitude and more distance. Records tumbled like dominoes, with each pilot vying to be the fastest, or the first.

In late 1947, Capt. Charles "Chuck" Yeager became the first person to break the sound barrier in a Bell-built experimental aircraft, the XS-1. That same year, the F-86 Sabrejet debuted in flight testing, and a B-47 Stratojet jet bomber flew for the first time.

The Air Force was racing into the jet age, and one important stop along the course would be 40,000 acres in middle Tennessee.

In 1954, a J47 engine, the power plant for the B-47 bomber, was tested at a simulated altitude of 30,000 feet in one of the first tests in an AEDC test cell.

Today, the B-47 – the predecessor of the B-52, B-58 and FB-111, as well as the KC-135 and Boeing 707 – is no longer flying but serves as a testimony to the beginning – the beginning of America's jet age and the beginning of AEDC's support to the warfighter.

Over the last 55 years, as new military systems were being developed, their components – engines, airframes, stores – made their way to AEDC facilities.

In the center's jet engine and rocket motor test cells; transonic, supersonic and hypersonic wind tunnels; and ballistic and impact ranges, AEDC engineers and scientists have pushed these systems to the edge in simulated flight.



# Military Flight Systems Timeline

## The 1950s

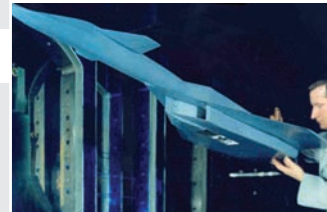


GAM-78 Quail

BOMARC  
B-47 Stratojet

T-38 Talon  
GAM-78 Quail

F-105 Thunderchief  
B-58 Hustler  
X-15  
F-5 Freedom Fighter  
XB-70 Valkyrie



XB-70 Valkyrie

## The 1960s



C-5 Galaxy

Dyna-Soar  
C-5 Galaxy

F-111 Aardvark  
E-3A Sentry

## The 1970s



AV-8B Harrier

Firebee  
A-10 Thunderbolt II  
X-24B  
F-117 Nighthawk  
X-24C  
F/A-18 Hornet

B-1 Lancer  
F-15 Eagle  
F-16 Falcon  
F-4 Phantom II

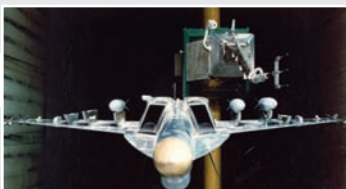


B-1 Lancer

YF-17  
Air-Launched Microfighter  
A-7 Corsair

C-141 Starlifter

## The 1980s



F/A-18 Super Hornet

AV-8B Harrier  
V-22 Osprey  
F-22A Raptor

F-14 Tomcat  
C-17 Globemaster III  
X-29  
YF-23

## The 1990s



F-35 Lightning II

X-30  
F/A-18 Super Hornet  
YF-36

B-52 Stratofortress

F-35 Lightning II

Dornier Alpha Jet  
B-2 Spirit  
KC-135 Stratotanker  
RQ-4 Global Hawk



F-22A Raptor

## The 2000s

EA-18 Growler

P-8A Poseidon



P-8A Poseidon

# F-105

## Thunderchief



The F-105 Thunderchief was a supersonic tactical fighter-bomber nicknamed the “Thud.” Armed with missiles and a cannon, the F-105 Thunderchief was designed to carry a nuclear bomb and fly at high speed and low altitude. F-105s were produced in the single-seated B and D series and in the two-seat F and G models. Later, some Fs were modified to become F-105Gs. The F-105D could carry more than 12,000 pounds of ordnance, a heavier bomb load than a World War II B-17. The F-105D was used extensively in the Vietnam War, flying 75 percent of the air strikes against North Vietnam during its first four years.

The Thunderchief was introduced May 27, 1958, and was retired Feb. 25, 1984.

### Highlights of Development Testing at AEDC

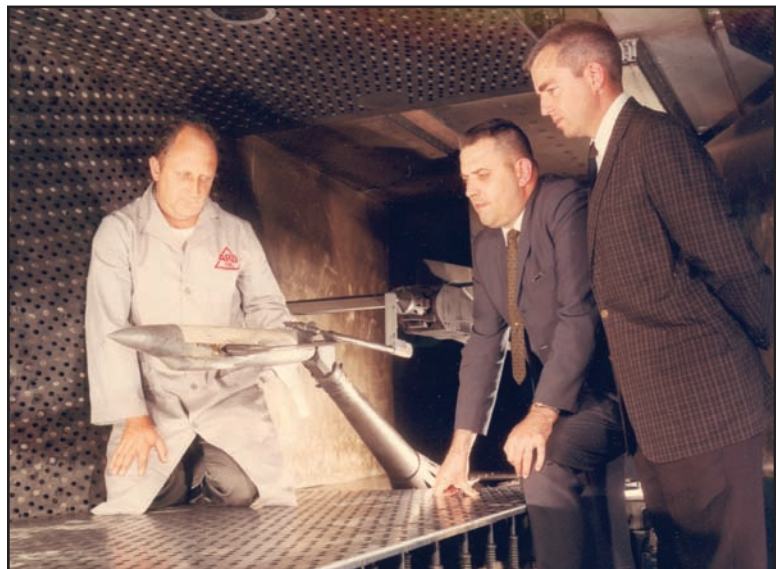
- Air inlet tests beginning in 1954
- Many store separation tests which included rockets, bombs and pods, under simulated combat conditions

Beginning in June 1954, tests were conducted at AEDC to determine the design and mass flow and pressure recovery characteristics through the supersonic range for an air inlet test. Inlet ducting tests for Republic Aviation Corporation’s F-105 Thunderchief fighter were conducted in tunnel E-1, the first major wind tunnel at AEDC to be placed in full operation. These tests made it possible for Republic engineers to improve the design and increase the aircraft’s performance.

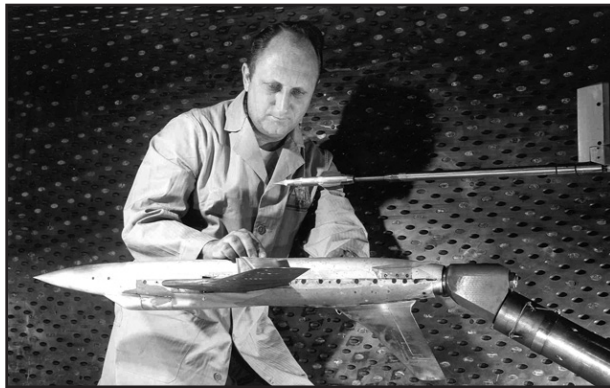
AEDC engineers investigated the F-105’s ability to launch or jettison various payloads of rockets, bombs and pods under combat conditions

### Characteristics

**Primary Function:** Fighter-bomber  
**Contractor:** Republic Aviation Company  
**Power Plant:** One P&W J75-P-19W  
**Thrust:** 23,500 pounds per engine  
**Wing Span:** 34 feet, 11 inches  
**Length:** 63 feet, 1 inches  
**Height:** 19 feet 8 inches  
**Maximum Speed:** 1,375 miles per hour  
**Maximum Takeoff Weight:** 52,838 pounds  
**Ceiling:** 48,100 feet  
**Range:** 2,200 miles  
**Crew:** One  
**Armament:** One M61 Vulcan 20-mm cannon and more than 8,000 pounds of ordnance  
**Date Deployed:** May 27, 1958  
**Retired:** February 1984



Trajectory characteristics of airborne armaments are determined by mounting a model of the parent aircraft in the wind tunnel test section in an inverted position. Electrical contacts tell operating personnel when the store is in normal carrying position on the actual aircraft.



**A model of the F-105 ready for test in 4T. The store model is held on a second support connected to a computer. Instrumentation in the store measures aerodynamic forces acting on the model, predicts a subsequent point on the trajectory and commands the drive system to place the store model in that position.**

in 1968. The F-105 was matched with an Air-to-Ground Missile (AGM)-12E air-to-ground guided missile and also with an airborne pod used to dispense a variety of munitions. The data collected from these tests were some of the first of their kind to be done at AEDC. The results were in agreement with the limited data that were available from flight testing or other wind tunnel studies at that time.

Wind tunnel tests were conducted in 1972 to determine separation characteristics of a rocket launcher from the F-105 aircraft in the center's 4-foot transonic wind tunnel (4T). The tests involved separation of full and empty rocket launcher models between Mach 0.4 and 0.9 at a simulated altitude of 5,000 feet. Data were obtained on six aircraft/weapons loading configurations with launcher releases from the left-wing inboard and outboard pylons of the F-105 model.

## **F-105 static display dedicated to General Bond**

The first aircraft to be put on static display at AEDC was dedicated to Lt. Gen. Robert M. Bond, vice commander of the Air Force Systems Command (AFSC), who was killed April 26, 1984, when the aircraft he was piloting crashed at Nellis Air Force Base (AFB), Nevada.

The F-105 Thunderchief is the type of aircraft General Bond flew in evaluation tests while he served as a test pilot at the Nellis Air Force Base Fighter Weapons School. General Bond also compiled 599 combat hours in F-105s while flying missions in Southeast Asia.

On hand for the AEDC dedication ceremony were General Bond's wife, Betty, and daughter Pamela Bond Lunger, as well as Lt. Gen. Bernard Randolph, who succeeded General Bond as Air Force Systems Command vice commander.

General Randolph called General Bond a "special breed" – a fighter pilot, leader and true patriot who loved the challenge and opportunity to serve his country in a special way.

"Underlying his qualities as an Airman and a leader was his personal commitment to the defense of our nation," General Randolph said. "This permanent display aircraft is a fitting tribute to the fighter pilot, the leader and the patriot that was Bobby Bond. May it serve as a lasting reminder of the man and the ideals that he represented during a long and distinguished career."

AEDC Commander Col. Philip Conran said General Bond had been a "leader and a friend" to AEDC and the Air Force Systems Command. He said the F-105 was chosen to commemorate

General Bond because it was his favorite type of aircraft and that the growth of the F-105 as one of this nation's leading air weapons systems closely paralleled the career of General Bond. Colonel Conran noted that the story of the F-105 began in 1951, the same year General Bond entered the aviation cadet program to earn his wings and commission.

After returning from a tour of duty in Southeast Asia, General Bond was assigned to Air Force Headquarters, where he worked to establish and validate operational requirements for tactical fighter and airlift aircraft.



**Right, Gen. Robert Bond. Below, the F-105 at AEDC was the first static display to be dedicated.**



# B-58

## Hustler

The Convair B-58 Hustler, America's first supersonic bomber, was developed for the Air Force during the late 1950s. Despite its sophisticated technology and Mach 2 performance, its operational flexibility was limited by changing mission requirements, which led to a brief career between 1960 and 1969.

Although its large wing made for relatively low wing loading, it proved to be surprisingly well suited for low-altitude, high-speed flight. It seated three (pilot, bombardier/navigator and defensive systems operator) in separated tandem cockpits, equipped with a novel ejection capsule that made it possible to eject at an altitude of 70,000 feet at speeds up to Mach 2.

### Characteristics

**Primary Function:** Supersonic bomber  
**Contractor:** Convair  
**Power Plant:** Four General Electric J79-GE-5A or -5B afterburning turbojets  
**Thrust:** 15,600 pounds per engine  
**Wing Span:** 56 feet 10 inches  
**Length:** 96 feet 9 inches  
**Height:** 31 feet 5 inches  
**Maximum Speed:** 1,321 miles per hour  
**Maximum Takeoff Weight:** 163,000 pounds  
**Ceiling:** 63,150 feet  
**Range:** 4,400 miles maximum ferry range  
**Crew:** Three  
**Armament:** One 20-mm cannon in tail; nuclear weapons in pod or on under-wing pylons  
**Date Deployed:** March 15, 1960  
**Inventory:** 116  
**Retired:** 1970



### Highlights of Development Testing at AEDC

- Development of the General Electric (GE) J79 turbojet engine
- Aerodynamic testing
- Development of high-speed crew escape capsule

The genesis of the B-58 program came in February 1949 when a Generalized Bomber Study had been issued by the Air Research and Development Command (ARDC).

The resulting B-58 design was the first "true" USAF supersonic bomber program. The Convair design was based on a delta wing with a leading-edge sweep of 60 degrees with four General Electric (GE) J79-GE-1 turbojet engines and was capable of flying at twice the speed of sound.

In 1955, the J79 turbojet engine began a development test program in the Engine Test Facility (ETF). On Oct. 6, 1956, AEDC completed the engine nacelle testing phase of the B-58 program after 142 hours, 29 minutes of air time in test Cell T-2 and 90 hours, 30 minutes of engine operating time.

The data made possible a greater understanding of the engine and helped accelerate the flight test program. Some early difficulties in control systems and compressor limitations were plotted for GE engineers, who promptly devised remedies or improvements.

One of the unique features of the B-58 was its crew escape capsules. Each crew member had a high-speed, high-altitude capsule that came down over them and encapsulated the crew when they ejected, something no other aircraft had.

In August 1959, the Hustler's supersonic escape capsule was tested in 16T. The purpose of the test was to determine what type of drogue chute provided optimum drag and stabilizing influence when deployed over a wide range of Mach numbers and altitudes.



The high-speed crew escape capsule was tested in 16T in 1961.



This model of the B-58 Hustler, the Air Force's first operational supersonic bomber, was tested in 16T.



# X-15

## Hypersonic Research Vehicle

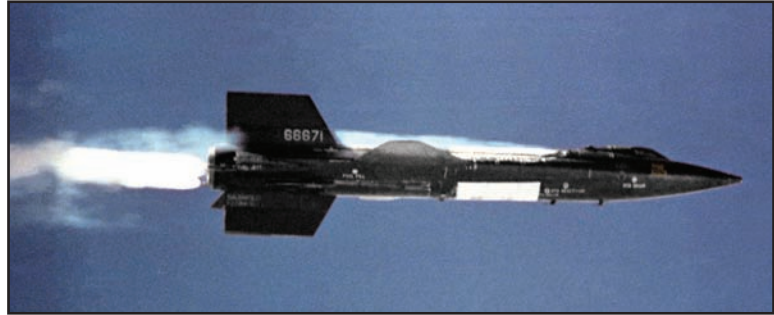
*The X-15, a rocket research aircraft, was a joint program by NASA, the Air Force and the Navy. Composed of an internal structure of titanium and a skin surface of a chrome-nickel alloy, the X-15 had its first, unpowered glide flight and powered flight in 1959.*

*Because of the large fuel consumption of its rocket engine, the X-15 was air launched from a B-52 aircraft at about 45,000 feet and speeds upward of 500 mph.*

*The X-15 program contributed to the development of the Mercury, Gemini and Apollo piloted spaceflight programs as well as the Space Shuttle program. The program's final flight was in 1968.*

### Characteristics

**Primary Function:** Prototype aircraft  
**Contractor:** North American Aviation  
**Power Plant:** Reaction Motors XLR-99 rocket engine  
**Thrust:** 50,000 pounds  
**Wing Span:** 22 feet, 4 inches  
**Length:** 50 feet, 3 inches  
**Height:** 11 feet, 7 inches  
**Maximum Speed:** 4,104 miles per hour (unofficial record)  
**Maximum Takeoff Weight:** 31,275 pounds  
**Ceiling:** 354,200 feet (unofficial record by X-15 No. 3)  
**Range:** 275 miles  
**Crew:** One  
**Armament:** None  
**Date Deployed:** Sept. 17, 1959  
**Built:** 3



### Highlights of Development Testing at AEDC

- Temperature and aerodynamic load testing

Almost 40 years ago, a U.S. aircraft called the X-15 achieved speeds and altitudes never before attained.

The airplane reached a peak altitude of more than 354,000 feet – more than three times as high as any other winged aircraft had achieved.

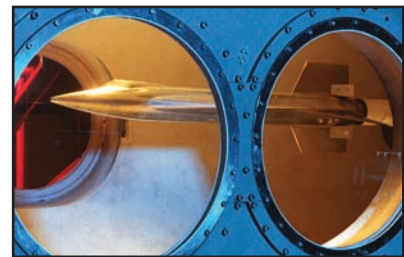
The X-15 shattered speed records when it exceeded 4,100 miles an hour. To this day, no other airplane has matched the records the X-15 has set.

The X-15 project began in 1952. The Air Force was assigned responsibility for administering the design and construction phases.

In the 1950s, AEDC provided aerodynamic tests that were instrumental in the development of the X-15.

In 1958, a 1/16-scale model of the X-15 underwent a series of high-speed and altitude tests in which temperature and aerodynamic load measurements were obtained in one of the center's hypersonic wind tunnels.

These data were valuable in support of our nation's manned space programs.



**The X-15 achieved what no other aircraft had. It attained an altitude of 67 miles and speeds in excess of 4,100 miles per hour.**



In 1966, North American test pilot Scott Crossfield, the first man to fly the X-15, was at AEDC discussing the record-setting aircraft. Crossfield helped design the X-15 rocket. He made 14 flights in the rocket plane, reaching Mach 2.97.

# T-38 Talon

*The T-38A Talon is a twin-engine, high-altitude, supersonic jet trainer used in a variety of roles because of its design, economy of operations, ease of maintenance, high performance and exceptional safety record. The T-38 can take off with as little as 2,300 feet of runway and can climb from sea level to nearly 30,000 feet in one minute.*

*First flown in 1959, the T-38 has undergone various airframe, engine and system components modifications or replacements under the Pacer Classic program, which integrates essential modifications and major structural replacements into one process. The basic airframe was used for the light combat aircraft F-5 Freedom Fighter family, which was also tested at AEDC.*

*Based on recent propulsion modernization, the T-38's service life should extend to 2020.*

## Characteristics

**Primary Function:** Advanced jet pilot trainer  
**Contractor:** Northrop  
**Power Plant:** Two General Electric J85-GE-5A turbojets  
**Thrust:** 3,300 pounds per engine  
**Wing Span:** 25 feet, 3 inches  
**Length:** 46 feet, 4 inches  
**Height:** 12 feet, 10 inches  
**Maximum Speed:** 812 miles per hour  
**Maximum Takeoff Weight:** 12,093 pounds  
**Ceiling:** Above 55,000 feet  
**Range:** 1,093 miles  
**Crew:** Two  
**Armament:** None  
**Date Deployed:** 1961  
**Inventory:** 462



## Highlights of Development Testing at AEDC

- Development of the T-38 through aerodynamic testing
- Bird strike testing of the aircraft's structure and canopy
- Environmental tests on the T-38's J85 engine

The Air Force's Air Education and Training Command uses the T-38C and the AT-38B (modified T-38A) to prepare pilots for front-line fighter and bomber aircraft.

The Talon first flew in 1959. More than 1,100 were delivered to the Air Force between 1961 and 1972 when production ended.

In 1958, prior to its first flight, the T-38 Talon underwent aerodynamic tests, including drag studies in 16T. Almost 20 years later, as part of a comprehensive Aeropropulsion Laboratory program to gain more knowledge of jet engine emissions on the environment, a J85 engine, which powers the Talon, was tested using a mobile pollution detector developed by AEDC.

The automatic instrumentation identified and measured both particulate and invisible gaseous emissions automatically, rapidly and consistently. Development included use of a remotely movable probe to sample emissions from idle through maximum afterburning to simulate taxiing, takeoff and landing. Concentrations of individual gaseous pollutants were measured and recorded automatically in near real-time with a probe as the engine was tested over a wide range of power conditions. Measurements obtained from the tests helped to identify the impact of jet engines on environmental quality.



The T-38 Northrop Talon supersonic jet trainer was tested in 16T in 1958. The first T-38 flew in 1959; it is still operational with the Air Education and Training Command and NASA.

In September 1981, the death of a member of the Thunderbirds, the Air Force's precision aerobatics team, was related to a bird strike. In taking off from an airport near Cleveland, Ohio, Lt. Col. D. L. Smith's T-38 reportedly struck a flock of seagulls, causing an explosion.

Since 1972, bird impact testing has been performed at AEDC on a number of Air Force aircraft components, including structures from the T-38 trainers.

In addition to launches against canopy samples, launches have also been made against flat steel plates to measure impact forces at various angles of attack and velocities. Samples of proposed windshield materials have also been tested for impact resistance. These tests helped engineers develop transparent materials that – although lightweight and optically suitable – are able to withstand high-impact forces without breaking, shattering or bending excessively.

During both 2007 and 2008, a long-standing collaboration between the Air Force Flight Test Center (AFFTC) at Edwards Air Force Base (AFB) and AEDC through its Technology and Analysis Program helped propulsion integration engineers quantify performance improvements of an updated version of the T-38. This partnership between the test centers is providing both near- and long-term benefits for the T-38 and all of its users. The analysis and evaluation provided by AFFTC and AEDC in conjunction with T-38C flight testing enhanced the decision-making process for the users in choosing the best aircraft configuration for the Air Education and Training Command.

An overarching goal of this collaboration was for the two centers to integrate ground test, flight test and modeling and simulation to reduce the time and cost of developmental testing and maximize knowledge derived from tests. AEDC engineers remotely supported T-38C/Propulsion Modernization Program tests at Edwards AFB. A tool used to analyze pressure, temperature and speed data from flight tests helped to determine where the compressor operated and to estimate the loss in stability pressure ratio caused by pressure and temperature distortion and Reynolds number effects. Engineers wanted to predict what flight conditions could possibly cause the compressor blades to stall.

The team discovered that the compressor speed measurement on the flight test aircraft did not respond



**The T-38 Northrop Talon supersonic jet trainer was tested in 16T in 1958. The first T-38 flew in 1959; it is still operational with the Air Education and Training Command and NASA.**

quickly enough to assess the loss in compressor stability margin during transient engine operation. Once they were alerted to the lag in the speed measurement, they were able to bypass the legacy speed measurement system on the production aircraft and use Edwards' signal-processing equipment to produce the high-quality, time-dependent data required for the Air Force's assessment of engine operability.

Even more important, the AFFTC-AEDC team was able to determine that the measurement uncertainty wasn't good enough to meet the test objectives prior to initiation of engine operability testing since recent upgrades to the T-38's engine and airframe challenged propulsion integration engineers. One goal of the propulsion modernization program was to get the highest possible performance out of the engine and aircraft without adversely affecting engine operability. The J85-5 engines in the T-38 aircraft do not have modern digital engine controllers like those found in the current generation of Air Force fighter engines. Without a full-authority digital electronic controller, compressor stalls can occur during aircraft maneuvers.

AEDC's role was to help characterize compressor operation during propulsion flight tests. Since safety of test and flight are critical and any instrumentation added to the engine has to be flight certified, few internal engine measurements are typically available in flight, and model-based analysis approaches are required to characterize compressor operation with a limited number of flight test measurements.

# F-5

## Freedom Fighter

*As a light supersonic fighter, the F-5 combined low cost, ease of maintenance and great versatility suitable for various types of ground-support and aerial intercept missions. The F-5, which resembles the USAF Northrop T-38 trainer, is suitable even for those missions which would have to be conducted from sod fields in combat areas. The F-5 was built around the smallest available engines, two afterburning General Electric J85s. The F-5, using the basic airframe of the T-38 trainer, first flew on July 30, 1959, and was delivered to the Tactical Air Command for instructing foreign pilots, in April 1964.*

### Characteristics

**Primary Function:** Fighter/Bomber  
**Contractor:** Northrop  
**Power Plant:** Two General Electric J85s  
**Thrust:** 4,080 pounds per engine  
**Wing Span:** 25 feet, 10 inches  
**Length:** 47 feet 2 inches  
**Height:** 13 feet, 6 inches  
**Maximum Speed:** 925 miles per hour  
**Maximum Takeoff Weight:** 24,664 pounds  
**Ceiling:** 50,700 feet  
**Range:** 1,100 miles  
**Crew:** One  
**Armament:** Two 20-mm cannons, rockets, missiles and 5,500 pounds of bombs externally  
**Date Deployed:** 1962  
**Inventory:** None left in USAF inventory; small number still in service with foreign air forces



### Highlights of Development Testing at AEDC

- Numerous tests on the F-5's propulsion system
- Testing of the F-5E version of the aircraft, which had a greater wing area, enlarged inlets and ducts, and a longer fuselage than the F-5 Freedom Fighter
- Testing an F-5G single engine version of the F-5

AEDC conducted numerous tests on the F-5's propulsion system. The J85 engine began testing in 1959, undergoing tests for environmental impact and simulating flight conditions for engine reliability.

General Electric's J85 engines have occupied the AEDC test cells and wind tunnels for more than 13,000 hours since the YJ85 prototype was first developed and tested at AEDC in 1959. Hundreds of tests were carried out, both on the engine alone and with it mounted in some of its intended vehicles.

In its initial qualification tests, the engine was subjected to all of the atmospheric, pressure and temperature conditions it encounters in actual flight. Temperatures ranging from 49 degrees below zero to 244 degrees



The F-5 underwent store separation testing in AEDC's 4-foot transonic wind tunnel in the early 1970s.



**A 10-percent scale model of Northrop's F-5G fighter was tested in 16T to define the aircraft's aerodynamic performance over a wide range of simulated altitudes.**

Fahrenheit, at altitudes from sea level to 65,000 feet and at speeds from zero to more than two and one-quarter times the speed of sound were simulated in the test cell. The J85-15 was subjected to starts, stops, restarts and coast periods to prove its ability to operate satisfactorily under all flight conditions.

In 1966, qualification tests of the engine, which the Canadian government planned to use in its CF-5 fighter aircraft, had been completed. The tests, which were conducted at the request of the State Department and the U.S. Air Force, were carried out under a variety of simulated altitude, temperature and environmental conditions in test cell T-2.

The F-5E jet fighter, also known as the International Freedom Fighter, was the first to use an automatic model attitude control system in AEDC's 16-foot wind tunnel (16T).

The use of the automated model in 1971 contributed immeasurably to completing the test program ahead of schedule.

The F-5E had a greater wing area, enlarged inlets and ducts and a longer fuselage than the F-5 Freedom Fighter. The F-5 underwent various store separation tests, and in the 1980s, tested a single-engine version, the F-5G in the Propulsion Wind Tunnel (PWT).

A J85 engine was subjected to simulated flight conditions of Mach number 1.6 at 55,000 feet and Mach number 2 at 65,000 feet at both military and partial afterburning settings.

Exhaust components of principal interest in this and earlier similar tests were carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, other oxides of nitrogen,

and all unburned hydrocarbons. Solid emissions were also measured in some of the tests through the use of gravimetric filters and electrostatic grids.

In 1975, an F-5 underwent separation studies carrying various types of stores in one of the center's wind tunnels.

Five years later, improvements in test equipment at AEDC reduced energy costs significantly during tests of the Northrop F-5G aircraft.

The tests, performed in 16T, defined aerodynamic performance, stability and control over a wide range of simulated altitudes and speeds. Northrop modified the F-5 aircraft to create the F-5G, which is powered with one engine rather than two.

Improvements in the transonic tunnel's sting support system, the apparatus that supports and positions the model in the test section, allowed engineers to move the model from one flight attitude to another at a faster rate.

By modifying the sting's computer control system and increasing the speed of the pitch drive motor, AEDC reduced the time required to move the model from one test position to the next from 21 to 11 seconds.

This resulted in a 16-percent reduction in electrical energy needed to operate the tunnel's 226,000 horsepower motor drive system – reducing the cost of obtaining the same amount of data by \$33,000.

When Northrop changed the inlet design of the F-5, tests on the improved version were conducted at AEDC to determine the most efficient air induction system design.

A total of nine configurations of the aircraft's inlets were tested in 16T at simulated flight speeds ranging from Mach 1.6 to 2.2 and simulated altitudes of 50,000 to 70,000 feet.

A 19-percent scale model of the Mach 2 export fighter was tested with varying lengths of the divider positioned between the two inlet ducts, ramp leading-edge extensions, various ramp bleed module arrangements, and environmental control system inlet extensions.

Inlet and duct line designs were tested to provide Northrop with data needed to choose the most desirable inlet system for the aircraft's single General Electric (GE) F404-GE-400 turbofan engine.

The 16,000-pound-thrust-class engine increased thrust by 60 percent over the 10,000 pounds of thrust produced by the J85 engines that power the F-5E/F. Tests provided engineers with data measuring inlet system performance and engine compatibility on all configurations.

The F-5G's inlets, located on each side of the fuselage, were enlarged slightly from those of its predecessor and were moved forward by several inches.

The inlets were moved outward from the fuselage to accommodate the thicker boundary-layer flow caused by the aircraft's increased speed.

The model was tested at angles of attack ranging from -4 to 16 degrees and angles of sideslip ranging from -2 to 2 degrees.

# XB-70

## Valkyrie

The XB-70 Valkyrie, with a planned cruise speed of Mach 3 and operating altitude of 70,000 feet, was to be the ultimate high-altitude, high-speed manned strategic bomber. To achieve Mach 3 performance, the B-70 was designed to “ride” its own shock wave, much as a surfer rides an ocean wave. The resulting shape used a delta wing on a slab-sided fuselage that contained the six jet engines that powered the aircraft. The outer wing panels were hinged. Two experimental XB-70A prototypes were under construction at North American Aviation when the program was canceled.

The No. 1 XB-70 made its initial flight on Sept. 21, 1964, and achieved Mach 3 flight on Oct. 14, 1965. The No. 2 airplane first flew on July 17, 1965, but on June 8, 1966, it crashed following a mid-air collision. The No. 1 airplane continued in its research program until flown to the National Museum of the U.S. Air Force on Feb. 4, 1969.

### Characteristics

**Primary Function:** Research aircraft  
**Contractor:** North American Aviation  
**Power Plant:** Six General Electric YJ93s  
**Thrust:** 30,000 pounds per engine  
**Wing Span:** 105 feet  
**Length:** 185 feet, 10 inches without boom; 192 feet, 2 inches with boom  
**Height:** 30 feet, 9 inches  
**Maximum Speed:** 2,056 miles per hour (Mach 3.1) at 73,000 feet  
**Maximum Takeoff Weight:** 534,700 pounds loaded  
**Ceiling:** 77,350 feet  
**Range:** 4,288 miles  
**Crew:** Two  
**Armament:** None  
**Built:** 2



### Highlights of Development Testing at AEDC

- Aerodynamic testing
- Engine/inlet integration

The XB-70 was one of the world’s most exotic airplanes. It was conceived for the Strategic Air Command in the 1950s as a high-altitude bomber that could fly three times the speed of sound.

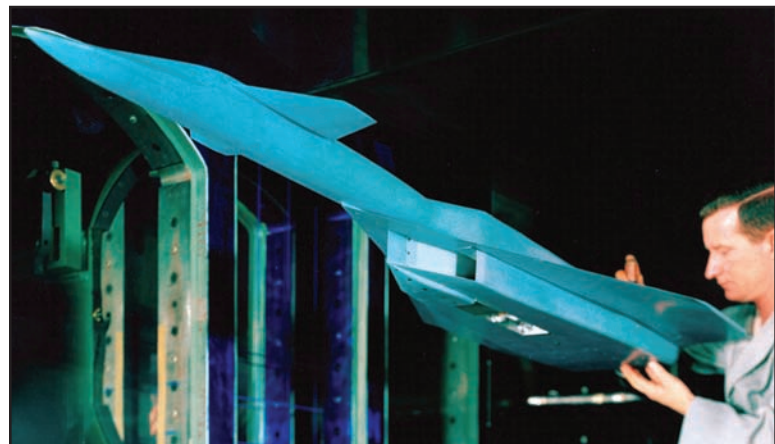
Because of fund limitations, only two were built, not as bombers but as research aircraft for the advanced study of aerodynamics, propulsion and other subjects related to large supersonic aircraft.

In 1960, an XB-70 development test program began in the Propulsion Wind Tunnel (PWT) facility; later tests required use of a 105-ton model, believed to be the largest ever tested in a supersonic wind tunnel.

A year later, J93 turbojet engine development tests were started in support of XB-70 development. The tests included a series with XB-70 test pilots at the engine controls.



The XB-70 engine inlet, about one-third of scale, was tested under simulated flight conditions in 16S with a J93 engine attached. The model weighed about 105 tons and is believed to be the largest ever tested in a closed-circuit wind tunnel.



A technician makes some necessary adjustments to a scale model of the XB-70. AEDC’s engineers studied the XB-70’s aerodynamic characteristics in Tunnel A.

# F-111

## Aardvark



The F-111 Aardvark, retired from U.S. service in 1996, is a multipurpose tactical fighter bomber capable of supersonic speeds and altitudes from tree-top level to above 60,000 feet. The F-111 has variable-sweep wings that allow the crew to fly from slow approach speeds to supersonic velocity at sea level and more than twice the speed of sound at higher altitudes. Full-forward wings give the most surface area and maximum lift for short takeoff and landing and the F-111 needs no drag chute or reverse thrust to slow down after landing. The USAF F-111 could carry conventional as well as nuclear weapons.

### Characteristics

**Primary Function:** Fighter/Bomber  
**Contractor:** General Dynamics  
**Power Plant:** Two P&W TF30-P103  
**Thrust:** 18,500 pounds per engine  
**Wing Span:** 32 feet swept; 63 feet extended  
**Length:** 73 feet, 6 inches  
**Height:** 17 feet  
**Maximum Speed:** 1,452 miles per hour  
**Maximum Takeoff Weight:** 92,657 pounds  
**Ceiling:** 57,000 feet  
**Range:** 3,632 miles  
**Crew:** Two  
**Armament:** one M-61A1 20-mm, plus a mix of up to 24 conventional or nuclear weapons  
**Date Deployed:** July 18, 1967  
**Inventory:** USAF: 0; Royal Australian Air Force: 24 F-111C  
**Retired:** 1996 (U.S.)

### Highlights of Development Testing at AEDC

- Support of the F-111 aircraft from cradle-to-grave
- Basic aerodynamic testing and evaluation of the airframe and store separation testing
- Testing of the aircraft's canopy for more than two decades as the system evolved

The development of the F-111 Aardvark began more than 45 years ago.

In 1962, General Dynamics (now Lockheed Martin) won a DoD contract to develop a supersonic aircraft called the TFX. This aircraft originally was expected to be a joint services fighter, operating both as an Air Force fighter and as an aircraft carrier-based Navy fighter.

This airplane was the first in history to incorporate features for performing in multiple roles. It was also to be the first production airplane with a “swing” wing – a wing configuration that can be changed in flight.

Production of the F-111 prototype began in the fall of 1963. In that same year, the first wind tunnel models of the F-111 were tested in AEDC's Propulsion Wind Tunnel (PWT) facilities and soon after the aircraft's Pratt & Whitney (P&W) TF30-P103 turbofan engines were being tested in the Engine Test Facility (ETF). The first F-111 rolled out on Oct. 15, 1964, 16 days ahead of schedule.

The following year, AEDC ran TF30-P103 engine inlet tests in PWT and store separation testing was also conducted in AEDC's 4-foot transonic wind tunnel facility at the same time.

The F-111 first flew in December 1964, and the first operational F-111



An F-111 wind tunnel model undergoes basic aerodynamic testing and evaluation in 16T in 1968.

## F-111 Aardvark



Above, left, the F-111 Aardvark was a unique aircraft in that the whole crew cockpit section became an ejection capsule. If the aircraft was going down and the crew had to eject from the aircraft, they ejected in the capsule, which became a lifeboat for them or survival station with radios and survival food rather than ejecting separately with ejection seats.



During the 1960s, the F-111 underwent bird strike testing at AEDC's "chicken gun."

was delivered to the Air Force in October 1967. During the rest of the decade, the F-111 went through many AEDC test cells, including PWT's 4-foot and 16-foot transonic wind tunnels (4T, 16T) and the 16-foot supersonic wind tunnel (16S), ETF and the Bird Impact Range, known as the "Chicken Gun."

The F-111 proved its versatility in the skies over Vietnam in 1972-73. A decade later, April 15, 1986, USAF F-111Fs from RAF Lakenheath, England, used the highly accurate Pave Tack laser-guided bombing system against terrorist targets in Libya.

In the early morning of Jan. 17, 1991, the F-111 went

into combat again in the initial bombing raids of Operation Desert Storm. More than 100 F-111 aircraft of different versions joined the first strikes against Iraq both as bombers and radar jammers (EF-111).

From the earliest days of the program to the 1990s, basic aerodynamic information was collected at AEDC.

In early 1963, the first wind tunnel models were tested in PWT. After the P&W TF30-P103 turbofan engines were tested in ETF, the propulsion system was integrated into the airframe. PWT again was used for engine inlet compatibility tests in 1964.

Almost two-thirds of the available test time in the 16S wind tunnel in 1964 was used in support of work on the F-111, culminating in the full-scale induction system program at the end of the year. The tests resulted in valuable design and operational data and also provided a firm foundation for the flight test program. From the standpoint of the AEDC equipment, the full-scale airframe engine test went relatively smoothly, thanks in large part to the center's previous experience with the XB-70.

During flight testing, the F-111 experienced store separation problems, and additional store separation work was conducted in 4T.



As the F-111's mission changed and it was required to operate at lower altitudes using terrain-following radar, the plane experienced several bird strikes. AEDC provided testing of the aircraft's canopy for more than two decades as the system evolved. AEDC helped develop the F-111E, with modified inlets and improved engine performance above Mach 2.2.

As part of the Air Force's "SEEK EAGLE" program, AEDC engineers used Computational Fluid Dynamics (CFD) to determine how a variety of stores – bombs, missiles or droptanks carried externally – would separate from the aircraft.

The F-111 had been modified from the 1960s to the 1990s and information about store trajectories was needed in the design of new stores and modifications of existing ones to ensure that they separated from the aircraft cleanly and stayed on their intended trajectories.

AEDC's role in conducting aerodynamic testing of the F-111 continued into the early 1990s.

Testers used a Lockheed Martin 1/15-scale F-111 aircraft model and small smart bomb models in 4T to collect test data on the munitions coming out of a supersonic internal weapons bay. They also examined new technologies to enhance separation characteristics of stores while reducing acoustic levels in the internal weapons bay.

One of the final AEDC aerodynamic tests of the F-111 was a model tested in 16T. AEDC engineers tested a 1/12-scale model of the Advanced Fighter Technology Integration/F-111. The model was configured with a mission-adaptive wing (changes shape for take-off, cruise, climb, etc.) and wing-mounted conventional and conformal stores.

In all, 563 F-111s in several variants were built. Seventy-six were built as FB-111s and saw service with the Strategic Air Command until 1990, when they were converted to F-111Gs and assigned to Tactical Air Command.

Former center commander and AEDC Fellow Maj. Gen. Lee V. Gossick was the F-111 System Program Director from 1967 to 1968.



Engineers from the Air Force Research Lab and the Royal Australian Air Force examine an F-111 aircraft and store model in 4T. Since 1960, AEDC has provided design and operational data critical to the F-111 flight-test program development.



An F-111 swing-wing fighter bomber scale model is checked out by an AEDC project engineer prior to a wind tunnel test in 1969.

# C-5 Galaxy



*The C-5 Galaxy, with its tremendous payload capability, provides the Air Mobility Command inter-theater airlift. The aircraft can carry fully-equipped, combat-ready military units to any point in the world on short notice and then provide the field support required to help sustain the fighting force. One of the largest aircraft in the world, the C-5 can carry outsize and oversize cargo intercontinental distances and can take off or land in relatively short distances. Ground crews can load and offload the C-5 simultaneously at the front and rear cargo openings.*

## Characteristics

**Primary Function:** Outsize cargo transport  
**Contractor:** Lockheed-Georgia Co.  
**Power Plant:** Four GE-TF39 engines  
**Thrust:** 43,000 pounds per engine  
**Wing Span:** 222.9 feet  
**Length:** 247.1 feet  
**Height:** 65.1 feet  
**Maximum Speed:** 518 miles per hour  
**Maximum Takeoff Weight:** C-5B 769,000 pounds (peacetime), 840,000 pounds (wartime)  
**Ceiling:** 34,000 feet  
**Range:** 6,320 nautical miles (empty)  
**Crew:** Seven  
**Armament:** None  
**Date Deployed:** C-5A - 1969, C-5B - 1980, C-5M-2009  
**Inventory:** Total force, 111

## Highlights of Development Testing at AEDC

- **Aerodynamic testing on the C-5 and the TF-39 engine powering the Galaxy**

American troops depend upon having the right equipment to defend our nation and carry out their mission.

AEDC's testing of the engine for the C-5 Galaxy heavy transport has helped to ensure that our troops have the tanks, armored vehicles and other heavy equipment needed to properly defend their posts for the past three-plus decades.

The GE TF39 engine, which powers the C-5A and C-5B Galaxy, completed propulsion flight certification in 1967 and was more recently tested in 2002. Aerodynamic test support began in 1965.

The C-5, one of the largest aircraft in the world, can carry outsize and oversize cargo intercontinental distances and can take off or land in relatively short distances. Ground crews can load and off-load the C-5 simultaneously at the front and rear cargo openings. The C-5 and the C-17 Globemaster III are partners in the Air Mobility Command's (AMC) strategic airlift concept. The aircraft can carry fully equipped combat-ready military units to any point in the world on short notice and then provide the field support required to help sustain the fighting force.

The first operational Galaxy was delivered to the 437th Airlift Wing, Charleston Air Force Base (AFB), South Carolina, in June 1970. Two years earlier, however, the C-5 was undergoing both propulsion and wind tunnel testing at AEDC. By March 1968, the C-5A transport had logged hundreds of hours of simulated flight time in model form during its development. Aerodynamic testing started in November 1965, only two months after the Air Force accepted the Lockheed design.

At that time, eight test series were conducted, involving the most sophisticated models tested in the center's then-15-year history. At the same time, AEDC was conducting the second phase of the aircraft's growth – environmental testing of its GE T39 turbofan jet engines.

The first C-5A tests in the Propulsion Wind Tunnel (PWT) facility were conducted after preliminary studies showed that the aircraft had more wind resistance, or drag, than desired. This series of tests aided Lockheed engineers in reducing this resistance by more than 30 "drag counts," a significant achievement, since each count above the anticipated total cut the plane's payload by 940 pounds.

Through 1966 and 1967, test objectives broadened to determining pressure distribution over the entire aircraft at various flight positions and speeds, investigating effects of control surface deflections, experimenting

with various motor suspensions and measuring forces acting upon the wings during thrust reverser operations.

As the tests grew more complex, so did the models. An early configuration contained 1,000 separate pressure-measurement points. In subsequent tests, this figure rose to 1,500 and finally to more than 2,100 in the most highly instrumented model ever installed in an AEDC wind tunnel at that time.

One model was only one side of the aircraft, but it had movable control surfaces and a miniature, nitrogen-driven turbine to simulate engine exhaust. Center engineers even mounted a model on an off-center support to make certain the usual model support was not interfering with the quality of the data being obtained.

Costs rose with complexity; one of the later models cost \$253,000. Data generated by the C-5A tests also set new center records for volume. One series produced some 30,000 printed pages, and in a two-week period as much data was recorded as was normally obtained in six months of operation in that tunnel.

While aerodynamic testing of the C-5A presented problems in sophistication, the Air Force faced a different problem in connection with environmental testing of its engine, since there was no facility in the country that could create the extreme flight conditions the TF39 would face.

The TF39 engine generates more than 40,000 pounds thrust, some four times that of a commercial jetliner engine of the era, and gulps air three times as fast. It must operate in air temperatures ranging from -65 degrees Fahrenheit to 135 degrees.

When GE first produced this engine, there was no test cell in the country capable of simulating the extreme flight conditions necessary to test it.

To build a suitable test cell from scratch would have required at least \$25 million and three years. Therefore, it was decided to modify the J-1 test cell, used previously to test the XB-70 jet engines.

The modification, costing \$6 million and requiring 18 months, was started soon after the first C-5A aerodynamic tests began. It included the addition of 5,600 tons of refrigeration capacity, provision for liquid nitrogen and liquid oxygen injection for further cooling, storage facilities for these liquid gases, expansion of the air supply system and extension of the cell itself. Modifications were completed in the fall of 1967, and the TF39 was installed in November.

By November 1969, tests to qualify the 43,000-pound-thrust TF39 turbofan engine were complete. Begun in December 1967, the test program acquired 230 hours of actual engine operating time on two engines.

The tests at simulated flight condition were roughly the equivalent of flying the engine at speeds from 0 to 670 mph and at altitudes from 15,000 to 50,000 feet.

The purpose of the tests was to ensure the satisfactory



**The GE TF39 engine for Air Force's C-5A transport is readied for qualification test in the J-1 engine test cell.**

performance of the engine at the altitudes, temperatures and speeds that it would encounter in actual flight. Early tests, conducted six months before the C-5A made its initial flight, showed that the development engine would meet the specifications and performance requirements of the Air Force.

When it was first mounted in the test cell on a pylon similar to the actual mounting on the C-5A, it was found that vibrations occurred that caused interference at the seal between the engine and the stationary inlet duct of the test cell.

With the ingenuity that characterizes the AEDC engineers and the flexibility built into the facilities, a solution to the problem was quickly found. By attaching four ordinary Volkswagen shock absorbers to the engine's inlet at the seal, a satisfactory "fix" was made, at a cost of less than \$20.

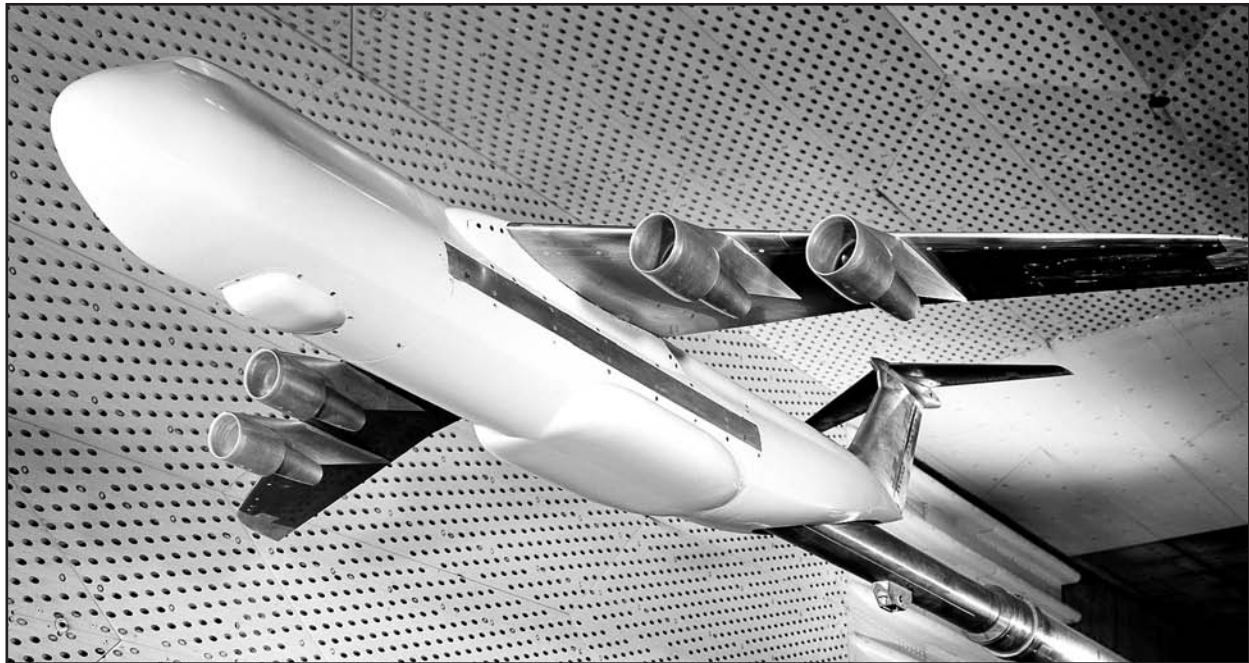
The TF39 was designed to operate most efficiently at a cruise speed of Mach 0.767, at an altitude of 36,089 feet.

In 2002, the TF39 was back at the center, this time for performance testing.

During that summer, GE's TF39-1C engine completed approximately 52 hours of testing during nine test periods in ASTF test cell C-2. The test objective was to determine how the engine fan responds to flight conditions.

The program had been a challenge for the testing team literally from the time the decision was made to conduct the testing in C-2. GE had to locate and refurbish TF39 test-enabling hardware that had not been used in years. AEDC provided extensive planning, design and fabrication for unique interface components to allow installation of the engine.

Testing was completed in approximately 39 hours of engine operation, during which AEDC recorded and



**Tests in 16T on the C-5 in 1965 helped Lockheed engineers substantially reduce drag in the final configuration.**

transmitted a large amount of formatted data to GE to support their analysis efforts.

During the test, the AEDC test team surveyed the flight envelope at increasing altitudes ranging from sea level to 40,000 feet, acquiring 452 data points characterizing the engine's response to multiple flight conditions and engine configurations.

To expedite testing, a team of AEDC and GE test operators went to Kelly AFB, Texas, to observe an engine checkout. The data recorded there were added to the data obtained at AEDC to provide a more complete overall picture of engine performance.

In addition to obtaining valuable telemetry data at sea-level conditions which otherwise would not have been collected, AEDC and GE personnel were able to identify and resolve numerous issues with both the engine instrumentation and data analysis/collection hardware.

The identification and resolution of these discrepancies before testing began at AEDC resulted in significant cost avoidance for the customer because of the potential cost of lost test time that could have resulted from these problems.

Using a prototype streamlined structural test data process, the team provided three "second-day" structural test data reports to GE and the Air Force.

This rapid report process took 70 percent less time and resources than previous AEDC structural test data reports and provided valuable and very timely information for both test direction and structural evaluation on the TF39 fan rotors.

In the later 1990s, the AMC began an aggressive program to modernize the C-5. The C-5 Avionics Modernization Program began in 1998 and included



**This was one of the C-5A test programs conducted in PWT that were cited by then General James Ferguson, commander, Air Force Systems Command, in support of his views on the continued development of aerospace testing facilities. The test model was a "semi-span" model at 1/18th scale. Included were the left wing with its two engines and half the fuselage. This model was wired up with over a thousand pressure sensors distributed around the surface and leading to remote recording devices.**

upgrading avionics to Global Air Traffic Management compliance, improving navigation and safety equipment and installing a new autopilot system.

Another part of the program was a comprehensive re-engineering and reliability improvement program, which included new engines, pylons and auxiliary power units, with upgrades to aircraft skin and frame, landing gear and the pressurization system.

# E-3A

## Sentry

*The E-3 Sentry Airborne Warning and Control System (AWACS) aircraft provides all-weather surveillance, command, control and communications needed by commanders of U.S., NATO and other allied air defense forces.*

*A modified Boeing 707/320 commercial airframe with a rotating radar dome, the E-3A provides an accurate, real-time picture of the battle space. AWACS provides situational awareness of friendly, neutral and hostile activity, command and control of an area of responsibility, battle management of theater forces, all-altitude and all-weather surveillance of the battle space, and early warning of enemy actions during joint, allied and coalition operations.*

### Characteristics

**Primary Function:** Airborne surveillance, command, control and communications

**Contractor:** Boeing

**Power Plant:** Four P&W TF33-PW-100A turbofan engines

**Thrust:** 21,000 pounds per engine

**Wing Span:** 145 feet, 9 inches

**Length:** 152 feet, 11 inches

**Height:** 41 feet, 9 inches

**Maximum Speed:** 360 miles per hour

**Maximum Takeoff Weight:** 347,000 pounds

**Ceiling:** Above 29,000 feet

**Range:** More than 5,000 miles (unrefueled)

**Crew:** Flight crew of four plus mission crew of 13 to 19 specialists

**Armament:** None

**Date Deployed:** April 1978

**Inventory:** Active force, 33



### Highlights of Development Testing at AEDC

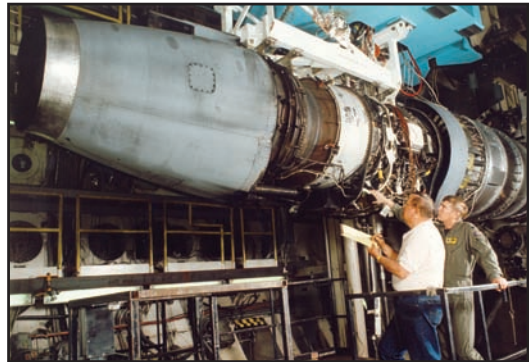
- **Aerodynamic tests on location at radar dome on the airframe**

During the late 1960s and early 1970s, the USSR began to pull ahead of the U.S. in the “arms race.” A limited budget for advanced and basic technology programs forced the Air Force to concentrate on high payoff areas, those exemplified by systems that would multiply the effectiveness of the existing force. With its testing to assist in the development of the E-3 Sentry airborne warning and control system (AWACS), AEDC helped support the idea of “doing more with less.”

In 1969, the E-3 Sentry underwent wind tunnel tests in the 16-foot transonic wind tunnel (16T). AEDC helped develop AWACS aircraft by testing scale models of proposed AWACS aircraft configurations.

The two competing models were a Boeing modified 707-320B and a McDonnell Douglas stretch DC-8. Testing took place in the Propulsion Wind Tunnel (PWT) facility to help determine exactly how the radar dome could best be mounted on the airplane.

The resulting data documented the drag and control characteristics resulting from the addition of the dome and its supporting structure. Boeing was awarded the contract in July 1970 for its 707 to carry the 30-foot-wide rotating rotodome.



The TF33, the power plant for the E-3A Sentry, has been tested in the center's Engine Test Facility.



A scale model of the AWACS was tested at AEDC in 1969 in 16T.

# B-1 Lancer

*The B-1A bomber was a multi-role swept wing aircraft capable of long-range bombing and missile launch, originally conceived in 1965 to replace the B-52 Stratofortress. The B-1B Lancer variant incorporated major changes, including an addition to the aircraft's structure to increase its payload by 74,000 pounds, improved radar sensor and the reduction of the aircraft's radar 'signature.' The engine inlet was extensively modified as part of this reduction, necessitating a decrease in maximum speed to Mach 1.2.*

## Characteristics

**Primary Function:** Long-range, multi-role, heavy bomber  
**Contractor:** Boeing, North America  
**Power Plant:** Four F101-GE-102 afterburning turbofans  
**Thrust:** 30,000 pounds per engine  
**Wing Span:** 137 feet extended forward, 79 feet swept aft  
**Length:** 146 feet  
**Height:** 34 feet  
**Maximum Speed:** 900-plus miles per hour (Mach 1.2 at sea level)  
**Maximum Takeoff Weight:** 477,000 pounds  
**Ceiling:** More than 30,000 feet  
**Range:** Intercontinental, unrefueled  
**Crew:** Four  
**Armament:** 24 GBU-31 GPS-aided JDAM or 24 Mk-84 2,000-pound general purpose bombs; 8 Mk-85 naval mines; 84 Mk-82 500-pound general purpose bombs; 84 Mk-62 500-pound naval mines; 30 CBU-87, -89, -97 cluster munitions; 30 CBU-103/104/105 WCMD, 24 AGM-158 JASSMs or 12 AGM-154 JSOWs.  
**Date Deployed:** June 1985  
**Inventory:** Active force, 65



## Highlights of Development Testing at AEDC

- **Supported a robust regimen of aerodynamic testing on the plane's airframe, engine, engine inlet and escape pod**
- **Conducted a range of store separation tests from the B-1A and B-1B Lancer**

The B-1A was initially developed in the 1970s as a replacement for the B-52. Four prototypes of this long-range, high speed (Mach 2.2) strategic bomber were developed and tested in the mid-1970s, but the program was canceled in 1977 before going into production. Flight testing continued through 1981.

Soon after Rockwell International and General Electric (GE) were selected in June 1970 as contractors for the airframe and engine, respectively, AEDC began supporting the program. By June 1972, the center was conducting simulated flight tests to help ensure clean separation of stores from the B-1.

The B-1B is an improved variant initiated by the Reagan administration in 1981. Major changes included additional structure to increase payload by 74,000 pounds, an improved radar sensor and reduction of the radar cross section (RCS) by an order of magnitude. The inlet was extensively modified as part of this RCS reduction, necessitating a decrease in maximum speed to Mach 1.2 at sea level.

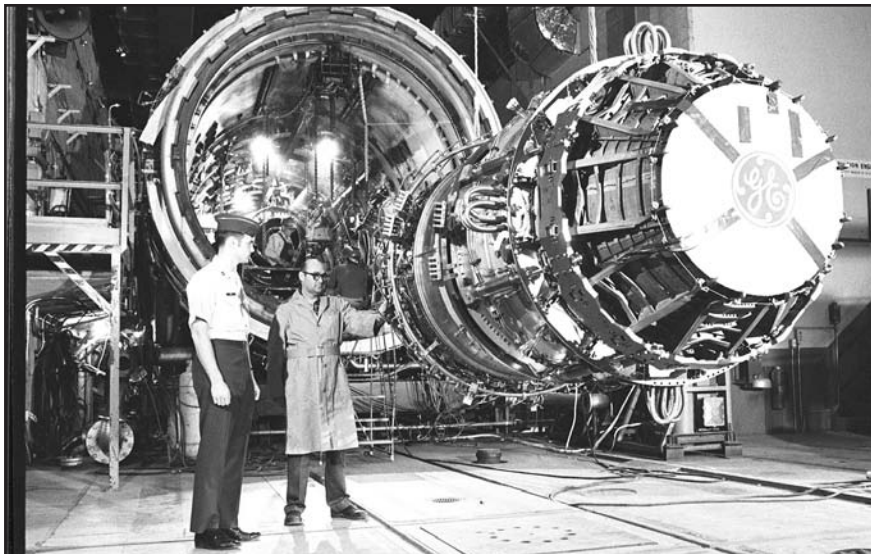
One test program provided data that were used in trajectory calculations that determined the separation characteristics of the Short-Range Attack Missile (SRAM) and conventional bombs from the weapons bays of the B-1 bomber. The tests were run in a supersonic tunnel in the von Kármán Gas Dynamics Facility (VKF) that simulated flight conditions covering a range of supersonic speeds and altitudes above 30,000 feet.

Continuing efforts in support of B-1 development included simulated tests in January 1973 to obtain data for use in determining engine nacelle-nozzle afterbody drag characteristics.

A 6-percent scale model of the B-1 was tested in both the center's 16-foot transonic and supersonic wind tunnels (16T, 16S) at various angles of attack. Eight different nozzles were tested to simulate various nozzle settings on the flight aircraft.

Tests of the model upright in the transonic tunnel were repeated with the model inverted to determine the magnitude of the flow generated on the nacelle-nozzle by the model support.

During 1973, AEDC heavily supported the B-1 test program.



Prototype configuration of a thrust augmentor (afterburner) for the GE F101 engine being prepared for installation in one of the center's high-altitude test cells.

Engineers at the center began tests to evaluate control requirements for the SRAM during launch. Using a 3-percent scale model in the 4-foot transonic wind tunnel (4T), they obtained data on separation characteristics at Mach numbers from 0.60 to 1.20 and at different angles of attack and sideslip. Wings were swept at 25 and 60 degrees with bomb bay doors at various positions. The SRAM model was mounted on a support system that required upside-down model installation for ease of handling.

Among the many tests conducted in support of the B-1 program were investigations of the crew escape capsule as it separates from the aircraft. A scale model of the capsule and part of the aircraft's fuselage were installed for testing in AEDC's 40-inch supersonic wind tunnel. The capsule was mounted on a remote-controlled support capable of movement in three directions.

Information obtained from AEDC's wind tunnel tests of scale models of the B-1 were used to help ensure that the design of the aircraft would provide the best performance possible at the speeds and altitudes at which it would be flown. A 3.6-percent scale model was tested in tunnels 16S and 16T at conditions simulating flight from 300 to 1,800 miles an hour at altitudes and attitudes the aircraft would encounter in flight.

Simulated flight tests to help ensure clean separation of stores from the bomber were also conducted in AEDC wind tunnels. This test program, which was conducted in the 40-inch supersonic tunnel (Tunnel A),

provided data used in trajectory calculations and in determining separation characteristics of the SRAM and the conventional iron bombs from the weapons bays of the B-1. Simulated flight conditions covered a range of supersonic speeds and altitudes above 30,000 feet.

Furthermore, high-speed dynamic stability tests of a 2.4-percent scale model of the B-1 were run at conditions simulating flight at various altitudes and speeds between 1,100 and 1,500 miles an hour. Supersonic tests were run with wings swept 55 and 67.5 degrees, and transonic tests were run with wings swept from 15 to 67.5 degrees.

By May 1973, prototypes of the engine for the B-1 had accumulated more than 300 hours of simulated flight time in 18 months of testing.

The B-1 program, which began in December 1971, involved testing the preliminary configurations of the complete engine at conditions simulating flight at various altitudes and speeds. Tests of the thrust augmentor (afterburner) alone were also run. Evaluation and comparison of data obtained aided in determining design of the production engine.

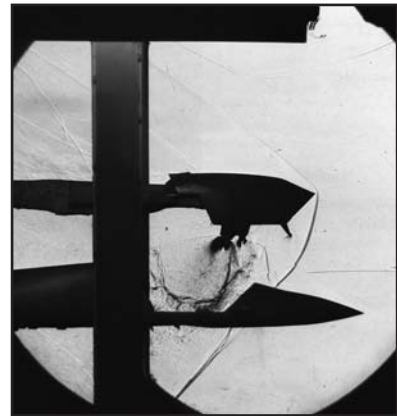
In AEDC tests, the engines were mounted on a thrust



AEDC engineers inspect the model as it is pitched to various angles of attack and roll prior to a test run. In 1972, the series of tests supporting development of the Air Force's B-1 advanced bomber involved this 6-percent scale model in 16S and 16T. The effects of model size were investigated by comparing data from the tests of the two differently scaled models as a basis for more accurate predictions of flight performance.



The B-1A crew escape capsule is mounted on a remote-controlled support capable of movement in three directions. The model was subjected to airflow at 1.5 and 2.25 times the speed of sound as the flow field around the capsule and simulated aircraft were studied.



This Schlieren photograph taken in a VKF tunnel shows the airflow around the capsule and the front section of the B-1A fuselage with simulation of exhaust from the rocket motors designed to lift the capsule away from the remainder of the aircraft.

stand, and turbulence-generating screens were used to simulate engine inlet distortions the B-1 was expected to encounter during flight maneuvers.

A highly complex instrumentation setup was used to measure such parameters as thrust, fuel consumption, combustion efficiency and reliability, vibration, control adequacy, restart limits, augmentor ignition and operation under test conditions simulating various flight environments.

Measurements made during the tests were fed directly into a computer, which processed the information to show precise engine performance. Much of the data was reported immediately to test crew personnel, who conducted the tests and regulated test conditions in the cell's control room. Based on this "real-time readout," certain data points were rerun to validate results or to investigate other engine performance characteristics.

Still photo and TV cameras were also used to monitor operation of the engine or to record special details such as views of afterburner combustion through a tailpipe periscope.

As in most of the engine development test programs conducted at the center, test data assisted the manufacturer in making a number of important refinements and improvements to the engine before full-scale production of the engine was begun.

By December 1973, a new external compression jet engine inlet being developed for the dual-engine nacelles on the B-1 strategic bomber had completed its first aerodynamic tests.

Two test series were conducted on the new inlet throughout the transonic speed range – one using a

7-percent model to measure drag attributable to the inlet and the other using a 20-percent scale model to examine inlet performance. Both were done in wind tunnel 16T.

Previous tests were accomplished with mixed-compression inlets. While physically similar to the original inlet, the new inlet slowed incoming air to less than sonic speeds before it entered the ducting connecting the inlet to the engine. In the earlier design, part of this slowing-down process was accomplished inside the inlet.

For the drag tests, a short section of wing complete with double-engine nacelle was supported on a balance to measure its resistance to air flowing round it. Measurements were taken with the inlet's movable ramps at various positions and at various simulated flight speeds.

These measurements were then compared with figures obtained from a shape that had minimum resistance to obtain a relative drag measurement for the inlet and nacelle.

For the performance tests, a large model of the B-1 fuselage complete with inboard wing sections was used. A full, working model of the double inlet was installed on one wing with suction applied to the rear of the engine nacelle to ensure proper airflow through the inlet.

At the same time that performance was being measured, noise levels in and around the bomb bay were also being examined. A battery of microphones recorded both the frequencies and the amplitudes with the bomb bay empty and loaded and with the bay doors open, partially open, and closed.

In February 1974, as a preliminary to full-scale tests, AEDC tested a 1/5-scale model of a large portion of the inlet in tunnels 16T and 16S.





Above, one of four air inlets to be used on the B-1 strategic bomber was assembled with the engine to which it will supply air prior to subsonic test. AEDC personnel devoted some five months to testing the engine/inlet combination to ensure their proper operation throughout the bomber's speed range. The extended section in the foreground represents the wing of the aircraft. Right, an AEDC craftsman inserts a scale model of the SRAM in the weapons bay of the B-1 for free-fall tests in the center's 40-inch supersonic wind tunnel. Tests were designed to verify North American Rockwell trajectory calculations.



These tests were performed in preparation for later tests in which the compatibility of an actual B-1 engine and its inlet would be determined. The 20-percent scale model was equipped with "cold flow" engine simulator, which were used to control airflow in the inlets to verify inputs to the computer control system that adjusts the geometry of the B-1's double inlets. These adjustments provided an adequate air supply for the engine during flight maneuvers.

The test data also were used to optimize the inlet's boundary-layer control, which helps prevent degradation in engine performance caused by excessive turbulence in the air supplied to the engine.

An additional aspect of the test series, which required 540 hours of tunnel operation, was a study of the effects on inlet performance of the B-1's weapons bay and ride control vane positions. The nose-mounted structural mode control vanes are designed to counteract the turbulence encountered at low altitudes and high speeds.

Inlet control variables – ramp angle, throat height, bypass door openings – were examined at speeds exceeding Mach 2 and simulated altitudes above 60,000 feet with the aircraft at various attitudes.

The compatibility tests were a major milestone in the development cycle of the supersonic bomber being produced by Rockwell International Corp. These tests ensured that the variable-geometry (adjustable) inlet would satisfactorily supply the proper quantity of air to the engine during all flight conditions and at various speeds and altitudes.

In the full-scale tests, an operating GE F101 engine was

mated with a complete inlet.

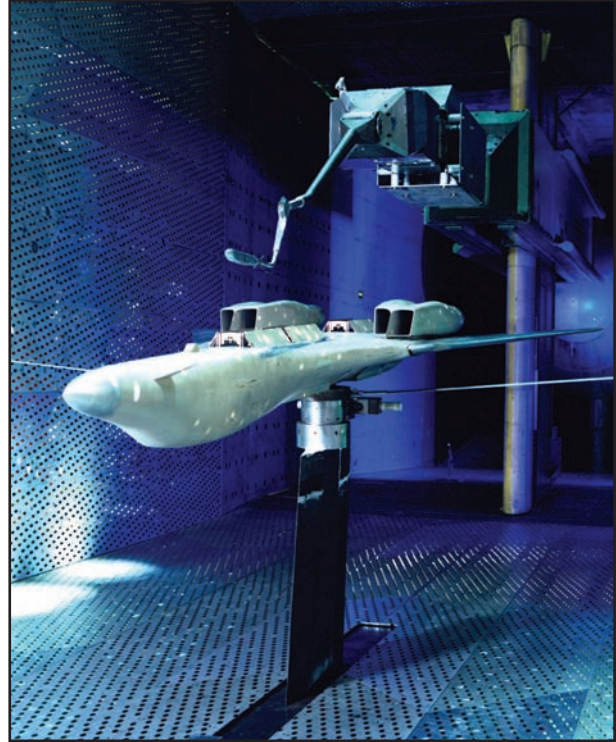
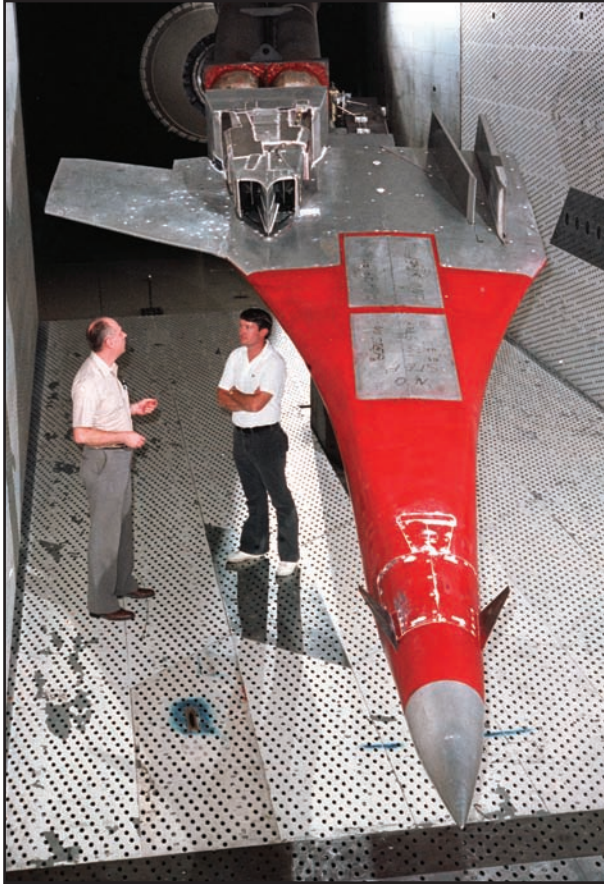
The F101 passed its preliminary flight rating test (PFRT) in April 1974 after approximately 80 hours of altitude testing at AEDC and 60 hours of endurance running at GE's plant near Cincinnati.

At that time, this PFRT was one of the most comprehensive ever conducted by the Air Force. It required a stringent demonstration of endurance on one engine at GE's plant, and altitude performance tests on a second engine at AEDC. The 29 components and associated systems were tested at various locations throughout the country.

The F101 endurance testing involved 10 running cycles of six hours each with rigorous cyclic and maximum power running at sea level and simulated high-altitude supersonic conditions. The engine was shut down, inspected and cooled for at least two hours between cycles. Following endurance testing, the engine was completely torn down for inspection by the Air Force. Altitude testing of the B-1 engine assessed performance, operability and stability. This segment of the PFRT required approximately 80 hours of engine running time.

Four of the 30,000-pound-thrust-class engines were installed on the first B-1 aircraft within the next few months. GE had already shipped one engine to Rockwell International's B-1 final assembly facility at Palmdale, California, to support the first flight of the aircraft later that year.

Wind tunnel tests to demonstrate compatibility between the air inlets and jet engines of the B-1 through the



Left, engineers discuss B-1B inlet testing at AEDC. Above, a 10-percent scale wind tunnel model of the B-1B Lancer is mounted from the floor inverted in 16T and a 10-percent scale Joint Standoff Weapon (JSOW) is mounted on a moveable support in preparation for separation testing.

subsonic and supersonic portions of its flight envelope were completed in July 1974.

The tests, in which a full-scale inlet of the Rockwell International-designed aircraft was mated with an operating GE-developed F101 engine, were an important part of the development program that had to be passed for the flight test program scheduled for later in 1974 at Edwards Air Force Base (AFB), California.

This compatibility testing was conducted in tunnels 16T and 16S.

Subsonic portions of the tests were completed in January, and the supersonic tests were finished in mid-April. The supersonic tests were divided into two parts – initial tests to compare the variable-geometry inlet's performance against data obtained at supersonic speeds with scale models, and final tests with the actual engine installed.

Slightly more than a month was devoted to testing the engine/inlet combination through the subsonic speed range. During that time, more than 70 hours of engine operating time were accumulated, including about 10 hours with the afterburner in use. Supersonic tests required more than two months to complete the two phases, with the inlet alone and with the engine/inlet combination.

Tests were conducted in January 1975 to further define

and possibly reduce the pressure oscillations inside open weapons bays of aircraft. The major objectives were the determination of oscillating pressure distribution in the bays, investigation of scaling effects, and the experimental verification of various methods designed to reduce the flow-induced oscillating pressure in the bays.

A 1/10-scale model of the forward portion of the B-1 was employed for the tests. Five different approaches for diverting the airflow over the open weapons bays were investigated. The diversion devices were installed either in front of or aft of the bays.

The tests were run at simulated flight speeds from 500 to 1,100 mph. Data were taken with the weapons bay doors open and closed, both with and without a full load of stores. Angle of attack and yaw angle were varied up to five degrees and to six degrees, respectively.

By the end of January 1975, tests of the B-1 bomber had accomplished two objectives at the same time. The large model of the aircraft's forebody incorporated the latest recommended modifications to save weight and/or drag in the engine inlets. At the same time, a pressure probe that would be used on the aircraft was mounted on the floor of tunnel 16S along with scale pressure probes on the B-1 model for direct comparison of data obtained. The probe became part of the sensing system that controls

the B-1's variable-geometry inlets. Because of the volume of the wind tunnel, the two tests were positioned to avoid mutual interference effects

A special series of tests using a flight test support F101 turbofan engine was completed in February 1975. The tests concentrated on afterburner operation and in-flight starting procedure. Afterburner operation was examined from sea level to 50,000 feet at speeds up to one and a quarter times the speed of sound (Mach 1.25). Starting procedures were looked at between 5,000 and 30,000 feet at subsonic speeds.

More than a year later, additional wind tunnel studies supporting development of the B-1 were completed. Tests looked at the effects of various fairings on the quality of airflow around the strategic bomber. Simulated flight speeds ranged from about 500 to 1,500 miles an hour. The effects of a redesigned aft radar housing also were examined. Oil flow and tuft flow visualization techniques



**B-1A crew escape capsule is readied for testing.**

were employed in the tests.

At approximately the same time, GE's F101 jet engine completed Product Verification (PV) testing, its final hurdle before the B-1 production decision.

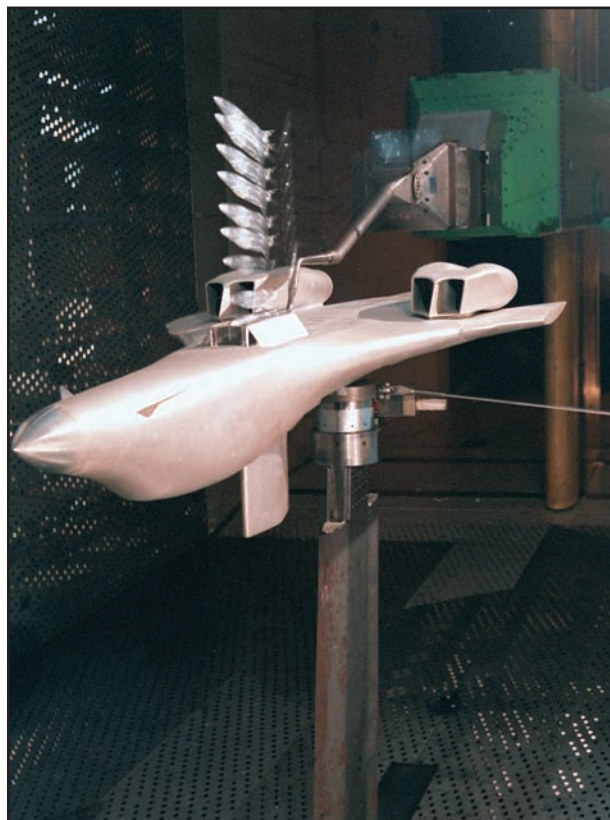
PV was a departure from past certification procedures for military engines. It replaced the old Military Qualification Test (MQT) and was structured after the actual planned use of the aircraft to simulate its service life more accurately.

The PV test matrix consisted of many component and complete engine tests – two of the most significant being endurance tests at GE's Evendale, Ohio, plant and the altitude performance test at AEDC.

Examined in the AEDC portion of the PV test program were the engine's performance under transient operating conditions as well as steady-state performance at several critical flight points; its surge and stall margins; air starts, both windmill and assisted; operation under icing conditions; and afterburner light-offs and performance. The afterburner portion of the program was conducted using a fuel schedule modified at AEDC on the basis of previous tests, resulting in greatly improved afterburner performance.

Completion of the PV tests was the fourth engine development hurdle involving AEDC under the Air Force's "fly-before-buy" approach being used in the B-1 program. The others were the PFRT and demonstration of compatibility between the engine and the aircraft's inlet, both completed in early 1974, and the F101 Critical Design Review (CDR) in mid-1975.

For more than four years, one of the high-altitude test cells in the center's Engine Test Facility (ETF) was devoted exclusively to the F101. Since the first B-1 left the ground in December 1974, AEDC tests have supported the development of the engine leading to PV; the Continuing Engineering Development (CED) program



**A multiple exposure photo of a SRAM II missile released from a one-tenth-scale model of the B-1B bomber during testing in 1974. The objective of the test was to see what path the missile would take after being released from the bomber. This type of testing, coupled with CFD studies greatly reduces the risk of in-flight accidents.**

## B-1 Lancer

after completion of PV; and the flight test program being conducted at Edwards AFB. The PV tests were completed about a week ahead of schedule.

As part of the design refinement process on the B-1 in 1977, a series of wind tunnel tests was conducted to examine the performance of various fairings designed to improve the quality of the airflow over the aircraft's wing where it joins the fuselage.

By the early 1980s, AEDC was once again testing the B-1, but this time it was on the next-generation version. Tests were aimed at rebuilding the nation's aging bomber forces by fielding the next generation multi-role bomber – a long-range, high subsonic version of the original B-1.

Because the external configuration of the B-1B would closely resemble that of its predecessor, the same B-1 model used for testing at AEDC in 1972 could be updated by the addition of nacelles and over-wing fairings and thus "recycled" for wind tunnel testing.

In the first of the three programs, 30 configurations of a modified 6-percent B-1 model were tested in 16T at simulated altitudes from 7,500 to 25,000 feet and at speeds ranging from Mach 0.6 to Mach 1.2 in order to determine the basic aerodynamic characteristics of the updated model. Air loads on the over-wing fairings were also measured to verify estimates made for structural loading.

Inlet verification tests, also performed in the 16-foot transonic tunnel, used 19 configurations of a 20-percent scale model to investigate aerodynamic interface plane (AIP) total pressure and distortion characteristics over the Mach range and maneuvering envelope of the aircraft.

A secondary objective, also met, was to obtain pressure data for use in predicting loads on new or modified inlet components. The variable engine inlets that enabled Mach

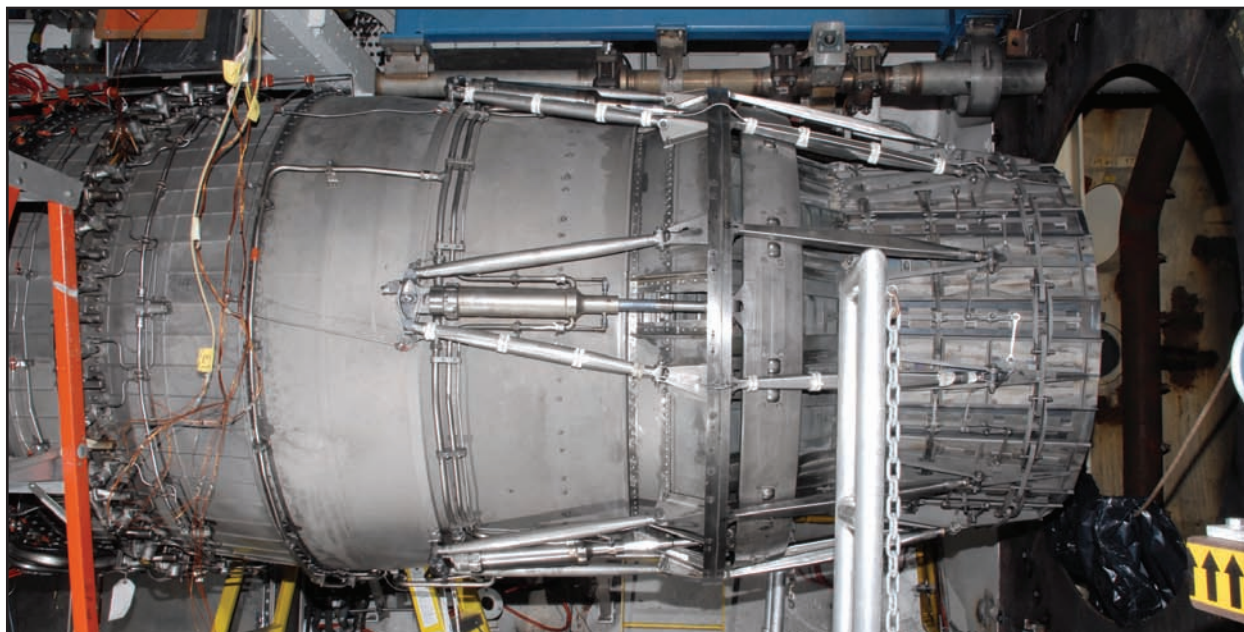
2 speeds by the original B-1 were replaced in the B-1B by fixed inlets optimized for the craft's high subsonic, low-altitude penetration mission.

A 3-percent scale model was installed in 4T for store separation testing. Aerodynamic loads were taken on in-bay carriage stores over a Mach range from 0.60 to 0.95 with the angle of attack varying from 0 to 8 degrees. Additional testing was done using the CTS and moving a sting-mounted store around within the flow field of the aircraft.

The F101-GE-102 was back at the center in June 2000 undergoing testing under simulated altitude conditions. The objective of the test program was to qualify a new Digital Electronic Control (DEC) module to replace the current analog, augmentor fan temperature (AFT) control module. Test data were acquired with the two engine control configurations to confirm equivalent engine operation throughout the flight envelope, at power levels up to maximum afterburner.

In the fall of 2007, AEDC conducted the first ground testing of the GE F101 engine using a 50-50 mix of Fischer-Tropsch (FT) synthetic and JP-8 jet fuels.

The F101 testing, conducted in J-1, was the first series to qualify a high performance, afterburning engine with F-T fuel for a combat aircraft. On hand to view the testing was then Secretary of the Air Force Michael W. Wynne, who said the Air Force's synthetic fuel initiative had already reached some significant milestones that year, including successful flight certification of the B-52 bomber, with technical support from Arnold, and successful qualification ground testing of the engine that powers both the C-17 and the Boeing 757.



The General Electric F101 engine was tested running on a 50-50 blend of Fisher-Tropsch synthetic fuel and JP-8 fuel.

# F-15

## Eagle

*The F-15 Eagle is an all-weather, extremely maneuverable, tactical fighter designed to permit the Air Force to gain and maintain air supremacy over the battlefield. The Eagle's air superiority is achieved through a combination of unprecedented maneuverability and acceleration, range, weapons and avionics. The weapons and flight control systems are designed so one person can safely and effectively perform air-to-air combat.*

### Characteristic F-15 Eagle

**Primary function:** Air-to-air (A/C/E) and air-to-ground (E) attack aircraft

**Contractor:** Boeing

**Power Plant:** Two Pratt & Whitney F100-PW-100, 220 or 229 turbofans

**Thrust:** 25,000-29,000 pounds per engine

**Wing Span:** 42.8 feet

**Length:** 63.8 feet

**Height:** 18.5 feet

**Maximum Speed:** 1,875 mph (Mach 2.5 plus)

**Maximum Takeoff Weight:** 81,000 pounds

**Ceiling:** 60,000 feet

**Range:** 3,450 miles ferry range with conformal fuel tanks and three external fuel tanks (A/C/D); 2,400 miles ferry range with conformal fuel tanks and three external fuel tanks (E)  
**Crew:** F-15C, one; F-15D, one or two; F-15E, two.

**Armament:** One internally mounted M-61A1 20 mm, six-barrel cannon with 940 rounds of ammunition; four AIM-9X Sidewinder and four AIM-7F/M Sparrow missiles, or eight AIM-120 AMRAAMs

**Date Deployed:** July 1972

**Inventory:** F-15 C/D: 437; F-15E: 223



### Highlights of Development Testing at AEDC

- Involved in early testing and evaluation prior to Air Force selection of the final McDonnell Douglas design
- Extensive full-scale engine inlet compatibility testing in large transonic wind tunnel
- Accelerated Mission Testing (AMT) of the F100 Super Pacer engine
- More than 23,000 hours of test time for all F-15 variant upgrades to the Pratt & Whitney (P&W) F100 engine in multiple altitude and ram air sea-level test cells
- Extensive use of Computational Fluid Dynamic (CFD) modeling for aerodynamics and store separation – first use of CFD on a major system

AEDC has been instrumental in the development of the F-15 from aerodynamic testing in the developmental stages of the system to engine testing and weapons separation testing of the various munitions systems the F-15 utilizes. The fighter has been extensively tested at the center since becoming operational in 1974.

The first production model of the F-15E was delivered to the 405th Tactical Training Wing, Luke Air Force Base (AFB), Arizona, in April 1988. One of the premier fighter jets in the Air Force inventory, the F-15 Eagle is an all-weather, extremely maneuverable tactical fighter designed to gain and maintain air superiority. The F-15E Strike Eagle is a dual-role fighter designed to perform air-to-air and air-to-ground missions. Its array of avionics and electronics systems gives the F-15E the capability to fight at low altitude, day or night, and in all weather.

Early in its development, before prime contractor McDonnell Douglas built the first experimental aircraft,



F-15 Eagle Short Take-Off/Landing demonstrator models were tested at AEDC for several years prior to the first flight in 1989. This 1985 photograph shows a model in 16T.

## F-15 Eagle

scale models of various configurations proposed for the F-15 were tested in AEDC wind tunnels to help determine optimal designs. Data helped engineers in making a number of design refinements to ensure optimum performance. Typical changes included such items as a more symmetrical radome, addition of cowl fences, changing the shape of the cowl lip, shifting the position of the wing and horizontal tail surfaces, modification of aft fuselage, removal of the tail, ventral fins and heightening of the vertical stabilizers.

One of the several milestones the F-15 aircraft met during its development was reached in tests in the 16-foot transonic and supersonic wind tunnels (16T, 16S). These tests demonstrated the compatibility of the



Seven F-15 design changes were verified in tests in 16T. AEDC did extensive support during the research and development stage of the F-15 program.

### Characteristics F-15 Strike Eagle

**Primary function:** Air-to-ground attack aircraft

**Contractor:** McDonnell Douglas Corp.

**Power plant:** Two Pratt & Whitney F100-PW-220 or 229 turbofan engines with afterburners

**Thrust:** 25,000 - 29,000 pounds each engine

**Wingspan:** 42.8 feet (13 meters)

**Length:** 63.8 feet (19.44 meters)

**Height:** 18.5 feet (5.6 meters)

**Weight:** 37,500 pounds ( 17,010 kilograms)

**Maximum takeoff weight:** 81,000 pounds (36,450 kilograms)

**Fuel capacity:** 35,550 pounds (three external tanks plus conformal fuel tanks)

**Payload:** depends upon mission

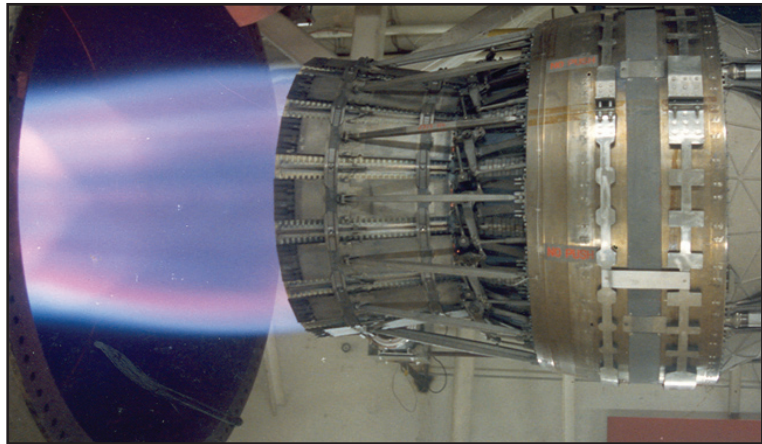
**Maximum Speed:** 1,875 mph (Mach 2.5 plus)

**Range:** 2,400 miles (3,840 kilometers) ferry range with conformal fuel tanks and three external fuel tanks

**Ceiling:** 60,000 feet (18,288 meters)

**Armament:** One 20mm multibarrel gun mounted internally with 500 rounds of ammunition. Four AIM-7F/M Sparrow missiles and four AIM-9L/M Sidewinder missiles, or eight AIM-120 AMRAAM missiles. Any air-to-surface weapon in the Air Force inventory (nuclear and conventional)

**Crew:** Pilot and weapon systems officer

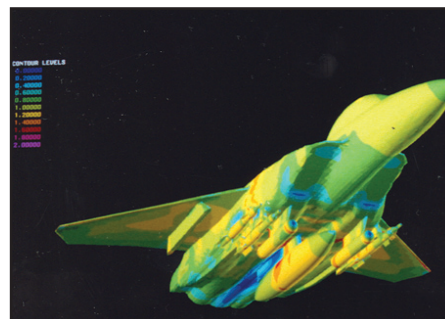
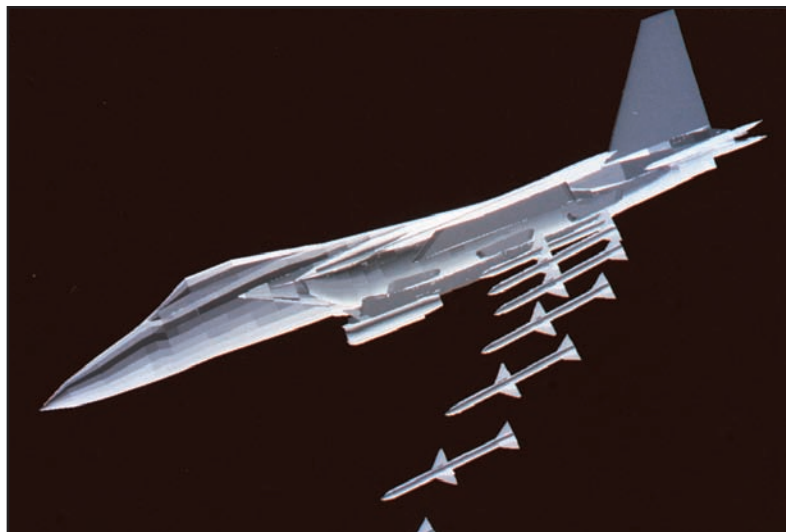


A Pratt & Whitney F100-PW-229 increased performance engine underwent RAM accelerated mission test. RAM refers to test conditions which simulate flight at the low-altitude, high-speed portion of a fighter aircraft's flight envelope.

F-15's Pratt & Whitney (P&W) F100 engine with the aircraft's variable geometry inlet prior to the F-15's first flight. Since the test section was not large enough to accommodate a full-sized nose section, a special fuselage segment was designed to produce inlet airflow conditions the F-15 would encounter in flight.

Three years later, advanced test techniques were employed in tests conducted in 4T to determine whether the F-15 fighter could jettison its auxiliary fuel tank in supersonic flight. The model tank was successfully free dropped from the parent aircraft. In addition to the free-drop technique, the wind tunnel's computer-controlled support system was used to measure forces on the fuel tank model to ensure that it would respond to these forces in the same way that the actual tank would when released. Later that same year, Sidewinder and Sparrow missiles as well as various air-to-surface stores were investigated at speeds ranging from about 450 to 1,000 mph.

Weapons separation tests in 4T were the first steps in certifying the Air-Guided Missile (AGM)-154A Joint Standoff Weapon (JSOW) and the Joint Direct Attack Munition (JDAM) Guided Bomb Unit (GBU)-31. (The GBU-31 JDAM possesses a tail kit developed to meet both Air



Above, a CFD image of an F-15E. Left, a computer-drawn mathematical model shows an AIM-7 Sparrow missile launch from an F-15E aircraft. Identical videotape footage of the event was shot during actual flight testing; the computer simulation was based on numerical data taken during wind tunnel testing at AEDC.

Force and Navy needs. It gives the weapon high accuracy in all-weather, day or night conditions.) The certification process can require up to 15 months. All wind tunnel testing for the F-15E-certified munitions occurred using 1/20-scale models. Aerodynamic force and moment data were measured in the flow field of the F-15E using the Captive Trajectory System (CTS). The CTS allowed for computer-controlled, six-degrees-of-freedom positioning of a missile, bomb or any other external store in close proximity to the aircraft model. Two types of store separation data – aerodynamic grid and captive trajectory – were obtained.

Aerodynamic grid data are obtained by forming a “grid” of measured forces and moments of the store at discrete positions or attitudes relative to the aircraft model. These data can be used to calculate a series trajectory when released from the aircraft.

The AGM-154A JSOW is an air-to-surface glide weapon armed with a warhead containing 145 BLU-97/B submunitions. Employed with a tightly coupled Global Positioning Satellite (GPS) Landing Systems (GLS)/inertial navigation system, it is capable of day, night and adverse weather operations.

Over the years, the F100 and its variants have been tested in six of the seven major cells in the Engine Test Facility (ETF). The T-cells have been the workhorse of the center’s altitude testing of the F100 engine throughout its history. Test cell J-1, complete with its 40-ton inlet simulator, supported the F-15 flight test program. The F100 was attached to the simulator, an engine/inlet simulator and turbulence generator designed to duplicate flow conditions the engine is expected to encounter in flight. The purpose of these tests were to help eliminate engine inlet incompatibility problems before the aircraft is flown. Flexible, metal-clad hoses and pipes provide airflow bypass and bleed ducting for the aircraft and the simulator. The

simulator was designed by P&W and was built by Humeic Tool and Die Company.

The F100-PW-100 engine was the initial engine installed in the F-15. Improvements to the -200 series produced the -220. Also tested on the -220 was the variable-pitch nozzle incorporated into the F-15 Short Takeoff and Landing (STOL) demonstrator fighter. Early development testing of the turbofan engine in AEDC’s T-4 engine test cell was conducted at simulated altitude, Mach number and power settings. Test objectives included sea-level functional and calibration tests, a windmill start program, fuel control development, a stability assessment program, engine and nozzle performance and a horsepower extraction test during windmill operation.

Special horsepower extraction equipment and high-response instrumentation supplied by P&W had to be



A full-scale F-15E inlet and operating engine were tested in 1972 in 16S. The tests demonstrated the compatibility of the F100 engine with the F-15’s variable geometry inlet.

## F-15 Eagle

installed in test cell T-4 to simulate the airframe power requirements during engine windmill conditions.

By 1973, AEDC testing had figured in all phases of the F100's development cycle, primarily because of the center's ability to provide the highest measurement accuracies over a wide range of simulated flight conditions.

Two competing engines in essentially identical high-altitude cells at conditions simulating flight at various Mach numbers and altitudes were tested in 1973.

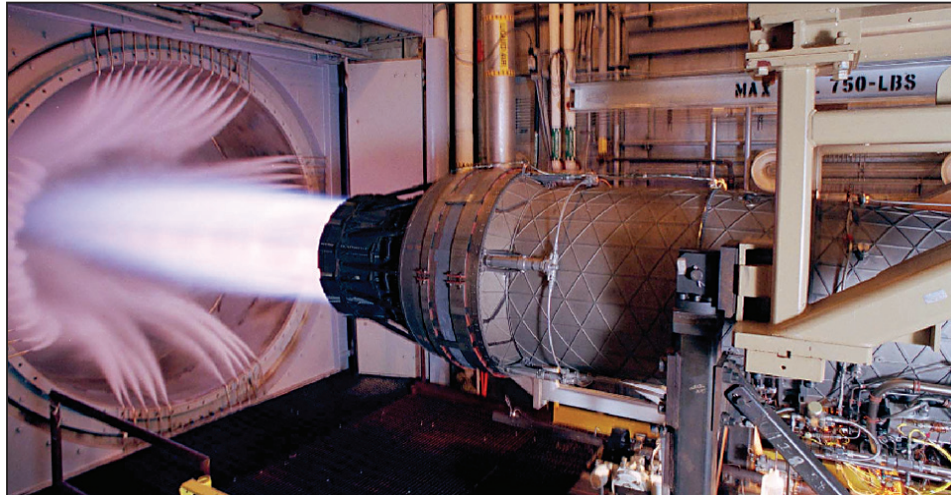
The F100 was used in test cell C-1 to support the checkout of the Aeropropulsion Systems Test Facility (ASTF) and appeared in test cell C-2 with a two-ton vectoring/thrust reversing nozzle.

The F100 engine was used to check out ASTF because of the volume of test data available on it and because it is a representative engine used by the Air Force's operational fighter fleet, which includes the F-15 and F-16.

AEDC successfully completed the first turbine engine RAM accelerated mission testing in 1992, using the P&W F100-PW-229.

New reversing and vectoring engines – those that have increased maneuvering capability – were tested for the first time by the Air Force in ASTF. The F100 engine was configured with a special 2-D convergent-divergent nozzle to confirm that the vectoring and reversing concepts were feasible.

In 1988, the F100-PW-229 Increased Performance Engine (IPE) completed Initial Flight Release (IFR) testing. IFR clearance of the F100 IPE required lengthy test periods – up to 22 hours – during which more than 900 engine parameters were recorded. The engine was subjected to simulated altitudes up to 50,000 feet and airspeeds at up to Mach 2. The F100 IPE is a highly evolved version of the F100 engine in service with the F-15 and the F-16. The IPE was designed to provide up to 29,000 pounds of thrust. The turbofan engine blades use a new, single-crystal material alloy that allows its two-stage, high-pressure turbine section to operate at higher temperatures for greater turbine efficiency. The engine also has an advanced version of the company's digital electronic engine control, which directly interfaces with



The P&W F100-PW-200 engine underwent sea-level RAM testing in test cell SL-2. Prior to the sea-level tests, the engine completed altitude testing in test cell J-2. AEDC conducted its first F100 test in 1969 and has supported development and component improvement ever since. RAM refers to test conditions which simulate flight at the low-altitude, high-speed portion of a fighter aircraft's flight envelope.



Store separation testing, using 5-percent scale models, began in 1985. More than 500 configurations have been investigated to ensure that the F-15E can safely deliver its wide array of weapons to accomplish its air-to-ground and air-to-air missions.

the aircraft control system. According to the manufacturer, this allows the aircraft and engine control systems to communicate with each other to automatically adjust performance as flight conditions vary.

By 1992, 5,000 Total Accumulated Cycles (TAC) were completed on the engine to substantiate the latest modification of its fourth stage turbine blades.

The F100 Super Pacer engine is an engine the Air Force pulled from the line to "lead the fleet." The engine underwent RAM accelerated mission testing (AMT) in 1996 to determine how the F100 engine will age.

(AMT has been in use by engine manufacturers for many years to rapidly age an engine within a few months



time. This ‘lead the fleet’ testing permits the manufacturer to accumulate several years of normal life in a very short amount of time, which allows the manufacturer to identify and attempt corrections to problems well before they occur in normal use. AMT is typically accomplished with an engine on an outdoor test stand and only requires a bellmouth to pull air from the atmosphere. RAM AMT is a variation of AMT developed by the Air Force to provide additional stress on the engine. The term ‘RAM’ refers to the use of test facility compressors to increase the engine inlet pressure and temperature to more closely simulate actual flight conditions.)

In 2001, testing in test cell T-1 validated proposed improvements to the P&W F100-220 engine in preparation

for flight testing.

An 18-month test phase assessed the engine’s increased stiffness, blades and oil seals and improved engine logic control systems. Using the Non-intrusive Stress Measurement System (NSMS), engineers measured the amount of blade deflection or bending that occurs during engine operation.

To accomplish this, the NSMS shines a laser beam through fiber optic cables onto the engine’s compressor. The light reflects from the fan blade back through another fiber optic cable attached to sensors outside the test cell. The sensors collect and read the data showing how much the blade bends during engine operations at selected flight conditions.

## F-15 Eagle at Arnold dedicated to fallen pilot

“The father is the hero, or he hopes to be. Jim was my hero,” said Art Duricy, the father of Major Jim Duricy, an Air Force test pilot who had an F-15 Eagle static display aircraft dedicated in his memory at Arnold on Aug. 9, 2007. “We are very proud of him - he never ceased to amaze me.

Duricy, with his wife, Irene, by his side, spoke those words to those attending the dedication ceremony. Those present included Major Duricy’s widow, Elaine Johnson, children, Erin and Kate, other family members, friends, guests, community leaders and AEDC contractor and military personnel.

Major Duricy was a 12-year test pilot who was killed when he was forced to eject at high speed as the F-15C he piloted crashed into the Gulf of Mexico on April 30, 2002.

The major was assigned to the 40th Flight Test Squadron, Eglin AFB, Florida, and was on a captive flight development test of a new air-to-air missile when the aircraft crashed. His body was never found.

Brig. Gen. C. D. Moore II, commander of the 478th Aeronautical Systems Wing, Wright-Patterson AFB, Ohio, was the guest speaker for the event. He is a command pilot with more than 3,000 flight hours in 30 types of aircraft. At the time of Major Duricy’s death, General Moore served as the commander of the 46th Operations Group at Eglin.

General Moore said that Major Duricy was the epitome of what makes the U.S. Air Force great.

“I really am humbled and grateful to be here today as we honor a fighter pilot, a test pilot, loving husband, father, devoted son and truly an outstanding American – Major Jim Duricy,” the general said. “It’s an honor to be here, not only to help dedicate this 46<sup>th</sup> Test Wing aircraft, but in recognition of the sacrifice Jim and his

family have made for our nation.”

The F-15C that was dedicated at AEDC was assigned to the 46th Test Wing, the same wing that Major Duricy flew with at the time of his death. The 46th is part of the Air Force’s Air Armament Center at Eglin.



Top, Maj. Jim Duricy. Bottom, Major Duricy’s family: parents Art and Irene Duricy; sister, Christine Benigar with her son; widow, Elaine Johnson and daughters, Erin and Kate, stand in front of the plaque honoring the fallen test pilot.

# F-16

## Fighting Falcon

*The F-16 is a compact and highly maneuverable multi-role fighter aircraft. Capable of performing air-to-air and air-to-surface attack missions, the F-16 has a long-range combat radius and can locate and destroy targets in all weather conditions. The F-16's design incorporates advanced aerospace technology and proven reliable systems from other legacy aircraft to simplify its design, reduce its size and production costs, and lower its purchase price and maintenance costs.*

### Characteristics

**Primary Function:** Multi-role fighter  
**Contractor:** Lockheed Martin  
**Power Plant:** F-16C/D: one F100-PW-200/220/229 or F110-GE-100/129  
**Thrust:** F-16C/D, 27,000 pounds per engine  
**Wing Span:** 32 feet, 8 inches  
**Length:** 49 feet, 5 inches  
**Height:** 16 feet  
**Maximum Speed:** 1,500 mph; Mach 2  
**Maximum Takeoff Weight:** 37,500 pounds  
**Ceiling:** Above 50,000 feet  
**Range:** More than 2,000 miles ferry range  
**Crew:** F-16C, One; F-16D, One or Two  
**Armament:** One M-61A1 20-mm multibarrel cannon with 500 rounds; external stations can carry up to six air-to-air missiles, conventional air-to-air and air-to-surface munitions and electronic countermeasure pods  
**Date Deployed:** January 1979  
**Inventory:** Total, F-16C/D, 1,280



### Highlights of Development Testing at AEDC

- **Extensive testing on the F-16 Fighting Falcon, and the Pratt & Whitney (P&W) F100-PW-200/220/229 and General Electric (GE) F110-GE-100/129 engines, as well as store separation investigations and work on a myriad of external munitions and payloads**

Before the first YF-16 made its inaugural flight test at Edwards Air Force Base (AFB), California, on Feb. 2, 1974, it had been flying in AEDC's wind tunnels since the beginning of the decade.

The General Dynamics version of the YF-16 that flew at AEDC in the early 1970s was a scale model and was, at that time, in a fly-off with the Northrop YF-17 for an Air Force lightweight fighter contract. The YF-17 also underwent testing at the center.

During the Vietnam Era, U.S. fighter aircraft had limited maneuvering capabilities at transonic speeds. This restriction resulted in an Air Force demand for an aircraft with transonic maneuvering capability and this stimulated the development of the Lightweight Fighter Program.

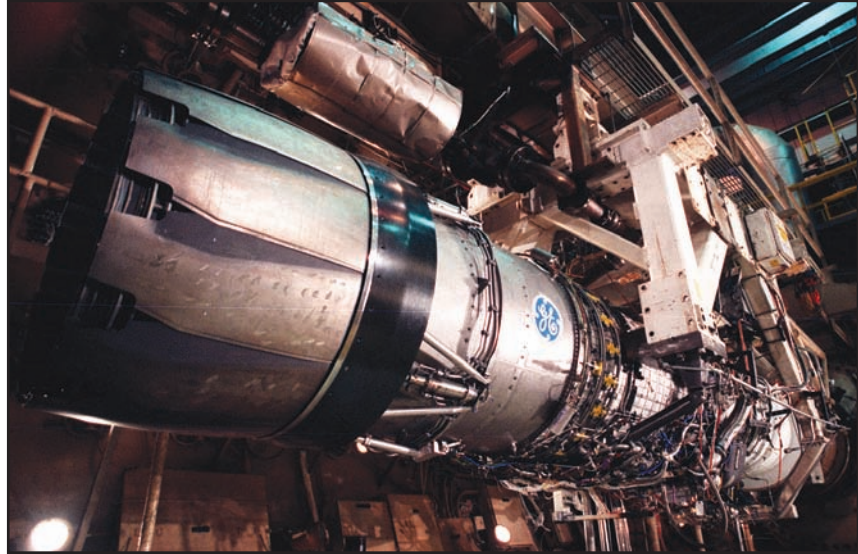
In January 1972, the Lightweight Fighter Program openly sought designs from several American aircraft manufacturers. Both General Dynamics and Northrop designed and built aircraft – the General Dynamics YF-16 and the Northrop YF-17 and AEDC tested the two contending aircraft.

Originally, no direct competition was scheduled. Both companies were given broad performance requirements to determine the feasibility of developing a small, light and low-cost fighter. Each was also responsible for evaluating advanced technologies and design concepts, determining their aircraft's capabilities, and establishing its possible operational utility.

Each firm was free to establish their own timetable. The General Dynamics aircraft rolled out in December 1973 and made its first flight in February 1974 at Edwards AFB. The first Northrop aircraft rolled out in April 1974 and made its first flight in June 1974, also at Edwards AFB.

In the early 1970s, AEDC conducted wind tunnel tests on a scale model of the YF-16 aircraft in 16T. The center also tested the jet engines that powered the fighters – the Pratt & Whitney (P&W) F100 for the YF-16 and the General Electric (GE) F110 for the YF-17. AEDC performed tests for both aircraft in their development phases and continued to support both aircraft in their operational stages.

The General Dynamics YF-16 was selected as the Air Combat Fighter and designated as the F-16.



**Left, last-minute adjustments prior to a wind tunnel test in 4T on an F-16 aircraft model configured with various store models. Right, the GE F110-GE-129 engine is shown in the J-2 engine test cell. The engine used improved materials and controls to increase performance up to 20 percent over the F110-GE-100 engine used in the F-16 Fighting Falcon. The tests simulated the full range of the engine's flight envelope up to Mach 2.5 and 65,000 feet altitude.**

The YF-17 would become the McDonnell Douglas F/A-18 Hornet for the U.S. Navy and Marine Corps. It continues to be tested in the center's wind tunnels in its latest version: the Boeing F/A-18 G Growler.

During 1974, AEDC remained intimately involved with the Lightweight Fighter Program, as evidenced by close to 400 occupancy hours for the program in the Propulsion Wind Tunnel's (PWT) 16-foot transonic and supersonic wind tunnels (16T, 16S). That was equal to about one out of every 10 test hours in the two large tunnels that year. (One of the YF-17 models that went through that testing is displayed in front of the PWT lobby area.)

In addition, the center conducted testing supporting two technology efforts involving the F-16: the Control Configured Vehicle program and the Advanced Fighter Technology Integration program.

The F-16A, a single-seat aircraft, first flew in December 1976. The first operational F-16A was delivered in January 1979 to the 388th Tactical Fighter Wing at Hill AFB, Utah.

In 1977, engineers were continuing store separation testing on a variety of external payloads from the F-16 in Tunnel 4T. Store separation testing was conducted on GBU-8 and GBU-10 air-to-ground munitions, the AIM-9J Sidewinder air-to-air missile, and the 370-gallon auxiliary fuel tank in various carriage configurations. The next year, 1978, store separation testing was conducted on an AGM-65 Maverick air-to-surface missile.

In addition to conventional wind tunnel testing, the center in 1979 conducted several tests sponsored by the Air Force Aerospace Medical Research Laboratory at Wright-Patterson, AFB, Ohio, to predict the aerodynamic forces that would be encountered by an F-16 pilot who had

to make an emergency ejection at speeds from Mach 0.4 to 1.5 (250 to 800 mph). The tests were also designed to predict cockpit conditions following canopy loss.

Finally, these tests were used to obtain data for use in designing windblast protective equipment for the pilots of F-16s and other aircraft.

Testing involved a half-scale model of the F-16's forebody and cockpit section with its canopy removed. This test article, with an instrumented model of a crew member positioned in an ejection seat, was tested in the tunnel.

Instrumentation recorded aerodynamic forces on the crewman as the seat was moved to various distances from the aircraft's open cockpit. These measurements were repeated using three different F-16 forebody configurations, including various arrangements of deflector plates intended to reduce windblast effects on a pilot during ejection from the aircraft. Three different crewman configurations were used: crewman in the basic seated configuration, the crewman with one flailing arm and the crewman with a flailing arm and leg.

The flight attitude of the model in the wind tunnel also was changed to simulate ejections while the aircraft was climbing or diving at angles of attack from -5 to 10 degrees and at sideslip angles of up to five degrees.

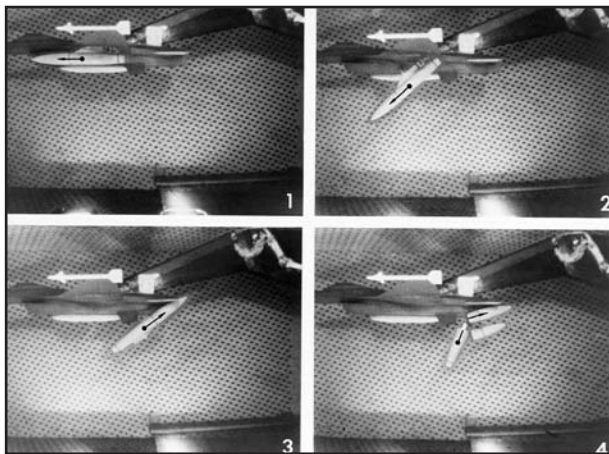
In 1982, AEDC conducted an external loads effects test of external navigational and targeting pods, including a Low Altitude Navigation Targeting Infrared for Night (LANTIRN) pod, on the F-16's inlet.

In 1987, the center conducted tests in 16T to gather data on the aerodynamic forces affecting a small female crew member who ejects from a model of an F-16. Female aircrew members, who at that time were limited to flight

## F-16 Fighting Falcon



Above, tests of a specially modified model of the General Dynamics YF-16 lightweight fighter were completed at AEDC. Two vertical control surfaces were installed on the model just aft of the engine inlet to enhance the aircraft's stability. The Air Force Flight Dynamics Laboratory requested use of one of the YF-16 prototypes after its flight evaluation program was complete so that they could continue research in the areas of control configuration and fly-by-wire controls, both concepts that were being incorporated into the YF-16 design. Right, aerodynamic forces on a half-scale model of an F-16 pilot during an emergency ejection were measured at speeds from Mach number 0.4 to 1.5 in 16T. Models of the aircraft without its canopy and of the pilot seated in an ejection seat were installed in an inverted position to facilitate adjustments during the tests.



Above, an F-16 store drop simulated in 4T resulted in a hit on the model's tail section. The photo sequence shows the store's release (1, 2), reverse, and impact with the aircraft model (3), and breaking apart, with the nose section splitting into two parts (4).

surgeons and flight test engineers, sit in the Advanced Concept Ejection Seat (ACES II) installed in the A-10, F-15, F-16 and B-1B aircraft.

Over the years, the F-16 has returned to AEDC's wind tunnels many times to qualify new stores for carriage and separation and to verify design changes before production.

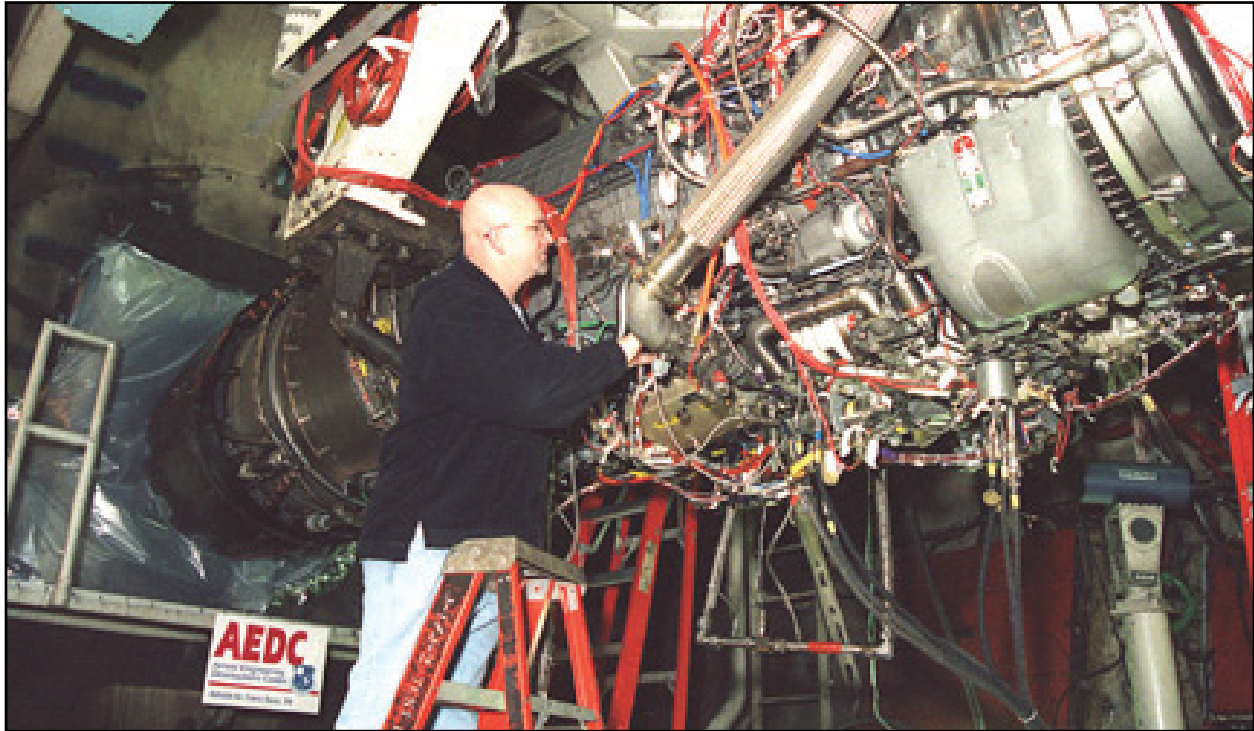
Over the years, AEDC's support to the F-16 program includes weapons separation testing. A test performed in 1997 in 4T provided data for the Air Force Seek Eagle Office, the Air-To-Ground Missile (AGM)-130 Office and the Joint Direct Attack Munitions Program Office at Eglin AFB, Florida. During this test, effects of variations of aircraft configuration, angle of attack, load factor, altitude, store center of gravity location, ejector characteristics and store roll release attitude on the data were evaluated.

In 1999, the F-16 was used in a Pressure Sensitive Paint (PSP) demonstration test in 16T. AEDC and Lockheed Martin sponsored the test to validate PSP techniques for measuring aerodynamic loads.

In addition to wind tunnel testing, the center has also extensively supported the two different jet engines that are power plants for the single-engine aircraft, the P&W F100 and the GE F110. Each engine has spent considerable time in AEDC's engine test cells over the last three decades.

While the P&W F100 fighter engine family began testing at AEDC in 1969, it was then primarily used to power the F-15 Eagle. The F100-PW-200 engine was the initial engine installed in the F-16.

In August 2001, AEDC concluded a 12-month test program in which a F100-PW-229 engine performed 3,503 sea level accelerated mission tests (AMT) and 988



An outside machinist checks components on the F110-GE-132 EFE engine during installation. The engine arrived at AEDC in 2001 after completing performance tests at GE's Peebles, Ohio, test facility and underwent about 220 hours of altitude testing in Test Cell J-2 to validate and qualify the engine performance. The 35,000-pound-thrust engine was chosen as the power plant for the Lockheed Martin Block 60 F-16.

RAM accelerated mission test cycles in the center's Sea Level Test Cells SL-2 and SL-3. (AMT has been in use by engine manufacturers for many years to rapidly age an engine within a few months time. This 'lead the fleet' testing permits the manufacturer to accumulate several years of normal life in a very short amount of time, which allows the manufacturer to identify and attempt corrections to problems well before they occur in normal use. AMT is typically accomplished with an engine on an outdoor test stand and only requires a bellmouth to pull air from the atmosphere. RAM AMT is a variation of AMT developed by the Air Force to provide additional stress on the engine. The term 'RAM' refers to the use of test facility compressors to increase the engine inlet pressure and temperature to more closely simulate actual flight conditions.)

The program's purpose was to obtain data on the engine's performance, durability and reliability during simulated missions. The program also included high-cycle fatigue testing to further validate engine hardware integrity.

Two years later, in the spring of 2003, the F100-PW-229 was back in SL-3. A team consisting of AEDC and P&W employees conducted 38 test periods simulating RAM AMT cycles, sea-level AMT cycles, high-cycle fatigue and component performance evaluations.

During these tests, crews operated the engine at extreme temperatures while demonstrating 1,583 total robust

accumulated mission cycles. The objectives of the testing was to validate the durability and integrity of the engine's hardware.

Testing of the GE F110 prototypes began at AEDC in 1979 with the altitude development testing of the F101DFE. By 1992, GE had brought 18 F110 and F110 derivative test projects to AEDC, purchasing some 2,500 testing hours at a cost exceeding \$32 million.

In 1999, the importance of flight simulation testing was proven in work conducted on the F110-GE-129 engine. The engine was experiencing a problem with burn-throughs in the engine liner. The engine liner is responsible for ensuring the extremely hot exhaust does not damage the internal components of the engine.

A burn-through could possibly result in the loss of an aircraft and the loss of an aircrew.

This test program re-established full maximum augmentor thrust – maximum thrust when using afterburner – for the engine by incorporating a redesigned exhaust liner and screech fix augmentor hardware.

One of the challenges to fixing the problem was predicting when a burn-through might occur. However, during testing, two liner burn-throughs happened while the engine was being operated and was observed in the cell.

From those observations, AEDC and GE engineers were able to design a fix for the engines that were then currently in the field.

# UAV

## Unmanned Aerial Vehicles



This model of the Ryan BQM-34B “Firebee” High-Speed Target Drone was tested in 16T in 1972.

Remotely piloted vehicles (RPV) used for combat, reconnaissance, training missions and other Unmanned Air Vehicles (UAVs) are playing an increasing role in maintaining the nation’s defense. Unlike manned aircraft, these vehicles can penetrate deep into enemy territory without risk to a pilot’s life and offer less costly alternatives in undertaking many military missions.

AEDC serves as a major testing facility in support of UAV development. Ground testing of UAVs is accomplished at AEDC at the flight conditions they will experience during a mission to help developers qualify the systems for flight, improve system design before production and troubleshoot problems with operational systems.

AEDC has nine major air-breathing engine test cells that have supported UAV testing. The test cells range in size from 7 feet to 28 feet in diameter and 9 feet to 85 feet in length and have thrust capacity up to 100,000 pounds. The test cells can simulate actual flight with pressure altitudes up to 100,000 feet, Mach numbers up to 3.8 and inlet total temperatures from -100 to 1,000 degrees Fahrenheit. In addition, three of the center’s major propulsion wind tunnels have been used for UAV testing.

Like all flight systems, UAVs go through several development stages – component development, integration and mission simulation prior to flight test. Mission simulation, however, has particular importance to UAVs since no automatic flight control system has the flexibility of a pilot to handle unanticipated flight problems.

In 1972, a model of the Ryan BQM-34B “Firebee” high-speed target drone was tested in the 16-foot transonic wind tunnel (16T). The Firebee was one of the first jet-propelled drones, debuting in the mid-1950s. In that same year, AEDC tested a 15-percent scale model of the Air Force’s jet target drone in the 4-foot transonic tunnel (4T). Stability and control data were obtained as the model, both with and without wingtip pods, was tested at conditions from Mach 0.6 to 1.3 at various angles of attack.

### Component Development and Qualification

Component development and qualification is done to address basic component performance. For engines, this includes thermodynamic performance, stability of the engine compression system and control authority and start reliability. Even for existing components adapted to new UAV uses, there is often some development testing required.

Of utmost importance is qualification of the UAV components according to the operational limits required by military applications. Ground testing allows analysis of a system in its entire operating envelope. This is particularly important when commercial systems are being adapted for military uses.

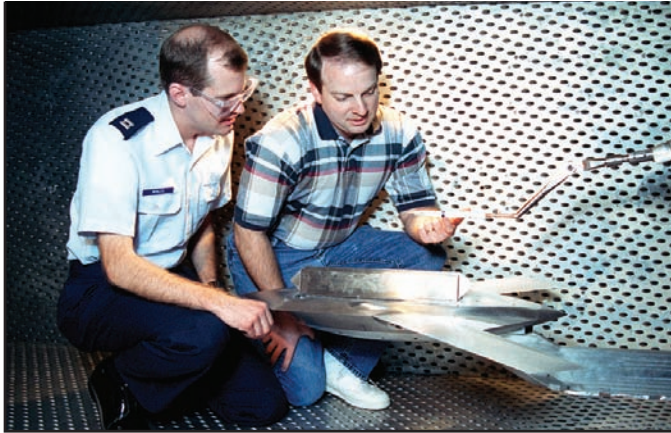
At AEDC, these systems are tested not only for extreme altitudes and Mach numbers, but under intense heat or cold, and in conditions such as dust or icing. AEDC tests also analyze conditions unique to military operations, such as use of alternative fuels, folding surfaces for aircraft stowage and carriage, extra power extraction for high-power electronics and vibration from ground, naval or air transport.

### Vehicle Integration

Once all the components have undergone extensive testing, AEDC tests the integration of all these components on the UAV. The integration effort is of particular importance for unmanned systems.

Small UAVs that use a single computer that simultaneously operates flight controls, sensors and the engine must be tested as an integrated vehicle to ensure proper system operation. On UAVs, aerodynamic and structural interaction between close-coupled engine and controls could cause catastrophic flight test failure. Ground testing can help pinpoint any such problem.

Ground testing at AEDC also explores integration of the aircraft with any stores (bombs or missiles externally



Engineers examine a 1/10-scale UCAV model undergoing store separation testing in 4T.

attached to the vehicle). Wind tunnel tests explore the trajectories of stores as they are released from the UAV at Mach numbers simulating actual flight. In addition, AEDC engineers use Computational Fluid Dynamics (CFD) to obtain detailed analyses of stores integration and other aerodynamic problems using sophisticated computer models.

### Mission Simulation

Mission simulation testing at AEDC evaluates the durability of the entire UAV under conditions that simulate actual flight missions. A UAV ground test mission simulation program at AEDC can greatly reduce the probability of major flight test failures and may also reduce the required number of developmental flight tests. Also, flight test failures can be evaluated in a controlled, repeatable environment at highly instrumented configurations to allow separation of variables that may be contributing to the problem. Mission simulation looks at typical vehicle mission profiles and various critical events during the mission as well as adverse environments to which the vehicle will be subjected.

UAV mission profiles review a wide variation in altitudes, speed and environments and may evaluate a vehicle's endurance and fuel consumption. A typical mission simulation may analyze starting, icing and cold operation, followed by avionics heating problems and low-altitude icing. Flight testing of such a complex scenario would be much more costly and would risk loss of the vehicle.

Mission simulation testing is used by the Air Force as part of competitive evaluations of different systems. For example, AEDC mission simulation testing led to the selection of the BGM-109 cruise missile partly because of its superior wind tunnel performance. This missile ultimately became the Navy's Submarine-Launched Ballistic Missile (SLBM).

There are a number of critical events in any UAV

mission that can negate a complete flight test program. Airstarts for ground or air launch must be reliable and result in stable thrust before the UAV hits the ground or becomes uncontrollable. Release from a carrier vehicle puts impulse loads on the UAV and pushes it through a very dynamic flow field. Wings and inlets, which are often deployed on UAVs, must be made reliable. Also, some UAVs have other transition points – such as from vertical to horizontal flight – which provide additional areas that must be examined. AEDC's simulation capability can remove much of the risk from these critical areas.

At AEDC, adverse mission environments can be simulated for complete UAVs. This includes tests on UAVs at extreme temperatures or under conditions such as icing, snow, water, dust and fog. These conditions could impact the sensors and radomes that are used to pilot the UAVs.

### Foundation for UAV Program

An AEDC ground test program for UAVs is designed as a foundation for a successful flight test. Ground testing can continue to support flight testing through mission dry runs to check out particularly critical missions and flight test problems can be resolved by recreating them in the controlled AEDC environment.

In 2000, Boeing began weapon separation ground testing of the X-45A Unmanned Combat Air Vehicle (UCAV) at AEDC in preparation to satisfy the Block 2 flight requirements. Wind tunnel data obtained in tunnel 4T played a valuable role in preparing the UAV flight tests.

The X-45A was the vision of the UCAV Advanced Technology Demonstration Program, a joint effort between the Defense Advanced Research Projects Agency (DARPA) and the Air Force. DARPA and the Air Force selected the advanced research and development unit of the Boeing Company, Phantom Works, to design and construct two subsonic UCAV demonstrator vehicles and conduct flight tests.

Stored in ready-to-ship containers until called into service, the UCAV system was envisioned to work cooperatively with manned weapon systems to suppress the enemy air defenses and strike missions in high-threat areas.

Using 1/10-scale models in 4T, AEDC testers obtained weapon separation data for several weapon types envisioned for use on the UCAV. Testers also obtained UCAV bay and bay door acoustical measurements and boundary-layer survey data in front of the bay.

The Air Force Research Laboratory (AFRL) used the data to help the organization's code developers do a better job of predicting weapons behavior and acoustic environment and as support for weapons development. AEDC conducted weapon separation testing in 4T in 2004 prior to a weapons check-flight of the X-45A.

# F-4

## Phantom II



*The F-4 Phantom was the first multi-service aircraft, flying concurrently with the U.S. Navy, Air Force and Marine Corps. An all-weather, twin-engine fighter-bomber, it was used by the Navy as an interceptor and by the Marine Corps in a ground support role. The F-4 was capable of performing three tactical airborne roles – air superiority, interdiction and close-air support – and was initially planned as an attack aircraft.*

*The F-4, which had a two-man crew, carried a wide variety of ordnance.*

### Highlights of Development Testing at AEDC

- Extensive store separation testing
- Validation of a number of pioneering test and data collection technologies and techniques, including the use of thermographic phosphor paint and the application of a light coating of oil to visualize airflow over the model during test conditions in the wind tunnel

### Characteristics

**Primary Function:** Tactical Fighter  
**Contractor:** McDonnell Douglas  
**Power Plant:** Two J-79-GE-15s  
**Thrust:** 17,000 pounds per engine  
**Wing Span:** 38 feet, 5 inches (27 feet, 7 inches folded)  
**Length:** 58 feet, 3 inches  
**Height:** 16 feet, 6 inches  
**Speed:** 1,400 miles per hour  
**Maximum Takeoff Weight:** 58,000 pounds  
**Ceiling:** 59,600 feet  
**Range:** 1,750 miles  
**Crew:** Two  
**Armament:** Up to 16,000 lbs of externally carried nuclear or conventional bombs, rockets, missiles or 20-mm cannon pods in various combinations  
**Date Deployed:** Dec. 30, 1960  
**Inventory:** Currently used as aerial targets - none operational for the U.S. More than 5,000 were built – more than 2,600 for the Air Force, about 1,200 for the Navy and Marine Corps and the rest for friendly foreign nations.

The history of the F-4 Phantom II began in the 1950s, when the fighter was developed by McDonnell Douglas for the Navy, as a carrier-based strike aircraft. The aircraft's performance and versatility were the best of its day, and the Air Force took note.

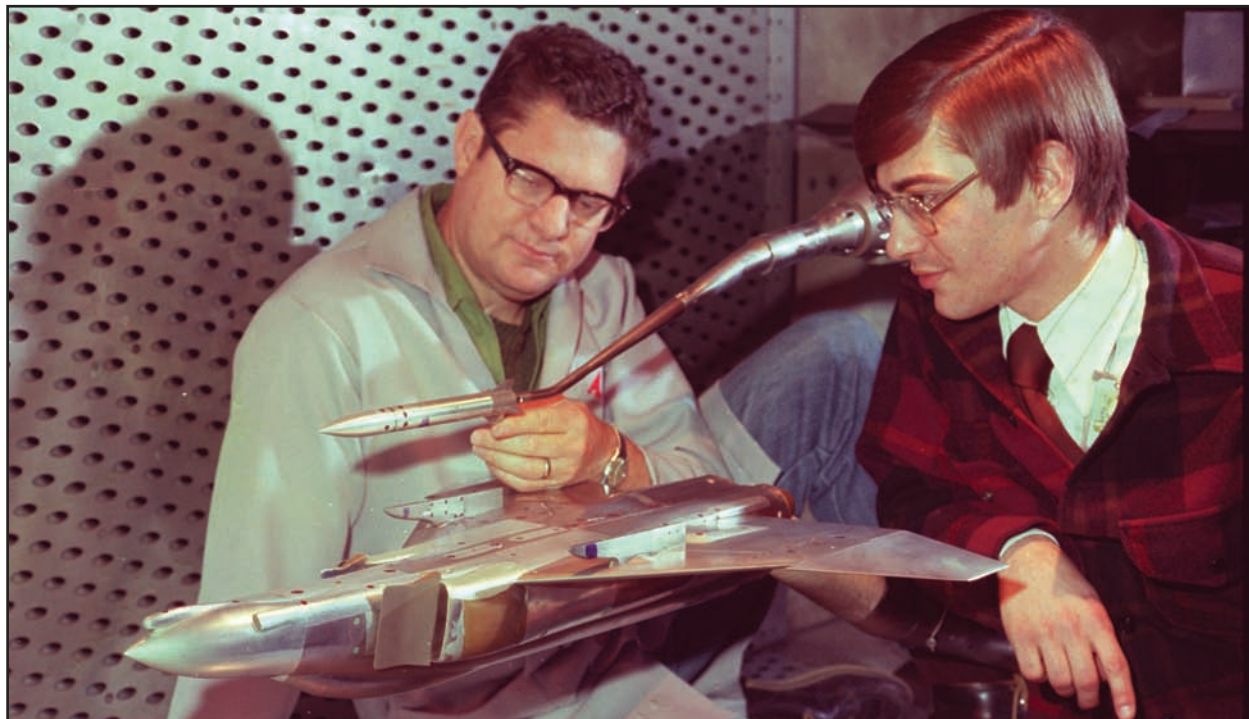
AEDC conducted extensive store separation testing from the F-4. The center's involvement with the F-4 also involved validation of a number of pioneering test and data collection technologies and techniques, including the use of thermographic phosphor paint and the application of a light coating of oil for visualizing the airflow over the model during test conditions in the wind tunnel.

On March 15, 1972, a scale model of the modified F-4E Phantom II jet fighter was tested in the center's 4-foot transonic wind tunnel (4T) to determine flight characteristics of bombs, fuel tanks and missiles dropped or launched from an aircraft that has wing leading edges modified to improve maneuverability. Flight forces were measured on a scale model store as it was gradually moved away from the inverted parent aircraft model.

A model was back in the wind tunnel in July for study of the aerodynamic effects of external stores on the fighter's flight characteristics. Scale models of advanced guided cluster weapons and external fuel tanks were mounted on the F-4 model to determine their effect on basic aircraft stability, drag characteristics and transonic trim changes. Conditions simulated flight at speeds from 300 to 950 mph at various angles of attack.

Wind tunnel tests of two testbed vehicles planned for use in evaluating new control and seeker systems for guided bombs were completed in January 1974. Essentially, the testbeds were a 700-pound guided bomb and a 2,000-pound guided bomb with full-length cruciform fins added. In both cases, the fins' leading edge were found close to the nose. On the smaller vehicle they reached full width in a single step, while on the larger





Testing in support of the Air Force's air-slew missile technology program entered its fourth year at AEDC in 1976. The program was aimed at investigating the technology required for an advanced air-launched missile capable of extreme maneuvers after launch. An F-4C Phantom model was mated in the center's 4T wind tunnel with a configuration representing the flight demonstration vehicle, a somewhat larger missile than the projected air-slew missile.

one, full width was achieved in three steps for aircraft carriage compatibility.

The three-part wind tunnel program at AEDC looked first at the aerodynamics of the two vehicles fitted with various fin shapes and sizes. With these determined, the second phase examined the aerodynamics of the F-4 Phantom, which would be used in the flight tests at Eglin Air Force Base (AFB), when carrying the vehicles on under-wing pylons. In the final segment of the program, AEDC's Captive Trajectory System (CTS) was used to study the vehicles' separation characteristics as they dropped from the aircraft at various flight speeds and altitudes. All three parts of the test program were conducted in 4T.

In September 1974, a 1/20th-scale model of an improved electronic countermeasures (ECM) pod being developed for the Air Force was tested using an F-4 as the parent aircraft in both phases of testing. (ECM pods are electronic devices that may be attached to aircraft to jam enemy radars.)

The purpose of the tests was to determine airloads on the aircraft and extended stores – the pod, a fuel tank and bombs – and to evaluate the effect of the pod on separation of the other stores.

Flight conditions ranging from Mach number 0.3 to 1.3 and altitudes from sea level to 30,000 feet were simulated during the tests, which involved 140 separation trajectories.

The wind tunnel test program was run to provide basic data to verify design of the pod and its suspension equipment and for planning a flight test program scheduled to begin later that year. Run in 4T, it was the first phase of testing concerned with the interaction of airloads on the pod, on adjacent stores and on the parent aircraft. The tests were run with the pod located at the left forward missile well and on the left-wing inboard pylon.

More than a year later, the F-4 was back in AEDC wind tunnels. Compatibility of the F-4 aircraft and the Guided Bomb Unit (GBU)-15 Planar Wing Weapon was studied in a series of tests. The Planar Wing Weapon is one of the GBU-15 modular air-to-surface guided munitions, a Mk-84 2,000-pound bomb fitted with a guidance and control module and an extendable planar wing module, including aft control surfaces.

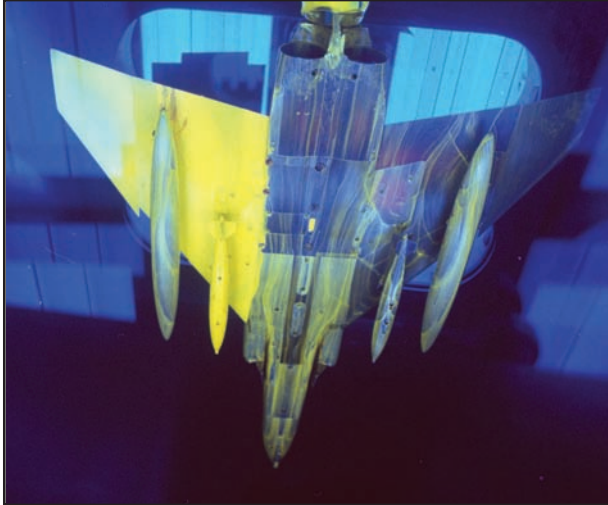
The tests were undertaken to assess any destabilizing effects of the munitions on the aircraft through the transonic speed range.

Ground testing in support of the Air Force's air-slew missile technology program went into its fourth year by June 1976.

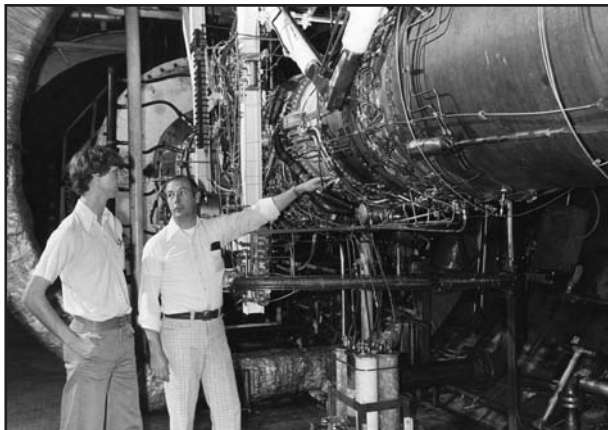
This program, designed to develop the technology for an advanced, air-launched missile capable of extreme maneuvers after launch, included an abrupt about face to intercept aircraft approaching from the rear.

Tests run in 4T were in preparation for forthcoming

## F-4 Phantom II



A combination of two wind tunnel techniques is shown during a series of tests using a model of the F-4 Phantom. The lighter colored area on the left wing is a yellow thermographic phosphor paint whose reflectance under ultraviolet light varies with temperature. The fuselage and right wing are coated with a light oil to which an ultraviolet dye has been added. The oil conforms itself to the air flowing over the model, making the streamline visible.



Engineers examine a J79 engine in the center's J-1 test cell. The engine, the power plant for the F-4, was first tested in the Engine Test Facility for the B-58 Hustler.

launches of a flight vehicle to demonstrate the air-slew principle. These performance verification tests were necessary to ensure that physical differences between the demonstration model and the actual missile would not adversely affect its performance. The tests would also provide engineers with information upon which to base their predictions of the demonstration vehicle's performance. The demonstration vehicle designed by Hughes Aircraft Corp. used an existing rocket motor, which caused it to be somewhat larger than the projected air-slew missile.

One test examined the behavior of the missiles after launch from an F-4C Phantom but still within the aircraft's

flow field. The wind tunnel's remotely controlled support was used to position the missile model at preselected grid points beneath the aircraft, where instrumentation measured aerodynamic forces acting on the model.

The support was also used in its automatic mode to simulate missile trajectories when launched at a variety of flight conditions. Starting from the normal carriage position, the controlling computer drove the support a given distance and direction from the aircraft. Forces were measured at the first stopping point, and the computer compared them with expected values. If they agreed, the model was moved another step along its trajectory and the process is repeated. If the values did not agree, the support was withdrawn one half the distance, and measurements compared to determine the next increment of the trajectory. The same tunnel was used to examine the aerodynamic characteristics of the missile without the influence of the parent aircraft. Together, these tests studied the missile throughout its 180-degree reversal maneuver.

Models of the F-4 were also used as a part of several research projects. One such project – an Air Force program supported by NASA – occurred in October 1976. The program was to develop a mathematical method to compensate for the effect of aerodynamic noise on wind tunnel data and thus to make the data correlate more closely with data obtained in flight tests.

This noise is generated as air is compressed and accelerated to high speeds as it passes through the tunnel's test section. Because many factors are involved, each tunnel has a different noise "signature."

If data could be adjusted to compensate for the noise, which would not be encountered in flight, wind tunnels would be able to simulate actual flight conditions more accurately, and tunnel measurements would come closer to those that would be recorded in flight.

Noise signatures for each of the tunnels had been determined by using a three-foot-long, high-precision conical model equipped with pressure and sound sensors.

The model was subjected to a variety of test conditions in each tunnel simulating flight at various altitudes and at speeds ranging from Mach 0.2 to 4.6.

Results were compared to establish the influence of aerodynamic noise on boundary-layer transition from laminar to turbulent on the model's surface at matched test conditions in the different tunnels. From these results an empirical correlation between transition and noise was developed, providing a scale for measuring the influence of the noise on aerodynamic testing.

Wind tunnel testing in preparation for the flight-test program was under way for two years. One test involved a 5-percent scale version of the conical model attached by a nose boom to a similarly scaled model of the Air Force's RF-4C jet aircraft. The cone/aircraft model was tested in the 16-foot transonic wind tunnel (16T), one of the tunnels

in which the full-scale cone had been tested previously.

The purpose of these tests was to ensure that the cone installation would not adversely affect the aircraft's stability and control at speeds from Mach 0.6 to 1.6.

In a later test in the same tunnel, another 5-percent scale model of the cone and RF-4C combination with the aircraft's flaps extended was tested at slower speeds to check flight characteristics during landing approach and takeoff.

These wind tunnel tests were run in preparation for actual flight tests, planned for following year, in which the full-scale cone would be boom-mounted on an RF-4C and flight tested at speeds up to Mach 2.

In 1979, part of a jet fighter's tail was tested in a wind tunnel to evaluate the operation of a hydromechanical

damper system designed to suppress the bending and twisting flutter effects encountered at critical flight conditions.

Although model constraints prevented simulation of critical flutter speeds, the test did demonstrate that advanced data analysis equipment could be used to determine flutter limits of flight surfaces without destroying them.

The test involved evaluating a full-scale right horizontal stabilator of the F-4 fighter at conditions simulating flight speeds from Mach numbers 0.4 to 0.95 and at altitudes from 4,000 to 44,000 feet.

The stabilator was mounted on a reflection plane from on a side wall in 16T.

A digital signal analyzer, programmed to produce integral damping calculations, was used in the tests.

## F-4C Phantom dedicated to fallen Airmen

After visiting Iraq, Afghanistan and Walter Reed Army Hospital, former Secretary of the Air Force Michael W. Wynne was overwhelmed by the military ethic of "standing watch so others may be free," exemplified by today's servicemen.

He faced a similar emotion when a Vietnam era F-4C Phantom II static display at Arnold AFB was dedicated in honor of his brother, Maj. Patrick Wynne, and Col. Lawrence Golberg.

"Pat believed with all his heart in what he was doing," Wynne said. "It was a life that was not lived, but well lived."

AEDC Commander Col. Art Huber's opening remarks reflected the meaning of the dedication event.

"Today our dedication is focused on those who flew the Phantom as much as it is on the aircraft itself," he said.

"We honor Colonel Golberg and Major Wynne, who answered their countries call and bravely flew into harm's way. Their payment of the ultimate price means

you and I can be here today at this ceremony remembering their contributions and remembering them as great Americans."

Colonel Golberg and Major Wynne were a part of the 555th Tactical Fighter Squadron, known as the Triple Nickel, stationed at Ubon Royal Thai Air Base when they were killed in action on Aug. 8, 1966.

The F-4C Phantom displayed at Arnold was, at one time, assigned to the 555th and is similar to the one they were piloting when they crashed in the Vietnamese jungle after a reconnaissance mission over North Vietnam.

The two pilots were listed as "Missing in Action" until 1977, when their remains were located and returned to the United States. Major Wynne's remains rest at the Air Force Academy, and Colonel Golberg's rest in his hometown in Minnesota.

As a further tribute to the men, two F-4s from the 82nd Aerial Target Squadron out of Tyndall AFB, Florida, performed a fly-by during the ceremony.



Above, left, Maj. Patrick Wynne. Middle, Col. Lawrence Golberg. Right, Col. Golberg's daughter Susan and his widow, Margaret, and Maj. Patrick Wynne's widow, Nancy Matalon, and brother and sister-in-law, Michael and Barbara Wynne, stand in front of the plaque honoring the fallen Airmen.

# F-117

## Nighthawk

*The single-seat F-117A Nighthawk was the world's first operational aircraft designed to exploit low-observable stealth technology. This precision-strike, subsonic aircraft could penetrate high-threat airspace and use laser-guided weapons against critical targets. About the size of an F-15 Eagle, the twin-engine aircraft was powered by two General Electric F404 turbofan engines and had quadruple redundant fly-by-wire flight controls.*

*The F-117A could employ a variety of weapons and was equipped with sophisticated navigation and attack systems integrated into a digital avionics suite that increased mission effectiveness and reduced pilot workload. The F-117 has been replaced by the F-22 Raptor. The first 117s were retired in May 2008.*



### Highlights of Development Testing at AEDC

- Extensive developmental testing in 16T
- Store separation testing from aircraft models in 4T

The F-117A Nighthawk, developed in total secrecy, was the first operational platform to employ what is known today as “stealth.” Its unconventional shape resembles something from a comic book but signified the arrival of a new era in fighter performance through low-observable technology.

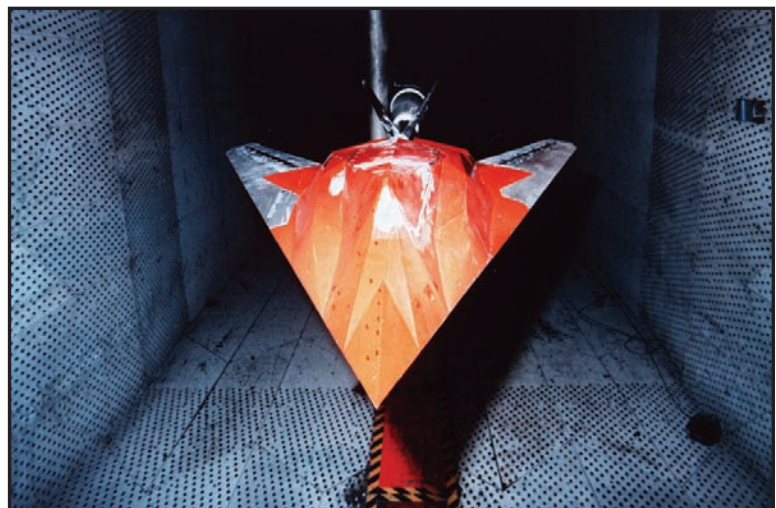
Unveiled to the public in 1990, the F117A is nearly undetectable by radar. This single-seat fighter is designed to penetrate deep into enemy territory and attack key targets with pinpoint accuracy.

About the size of an F-15 Eagle, the twin engine aircraft is powered by two General Electric (GE) F404 turbofan engines and uses computer-operated fly-by-wire flight controls to maintain the aircraft's stability.

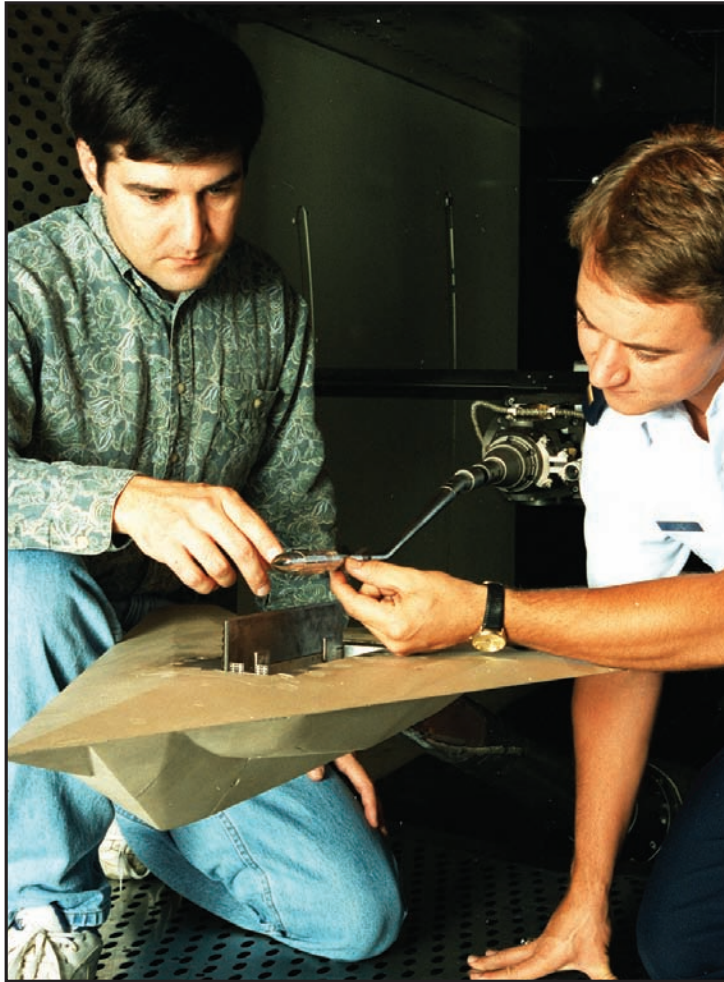
The decision to produce the F-117A was made in 1978 with the contract

### Characteristics

**Primary Function:** Attack aircraft  
**Contractor:** Lockheed Martin  
**Power Plant:** Two General Electric F404-GE-F102 non-afterburning engines  
**Thrust:** 10,600 pounds per engine  
**Wing Span:** 43 feet, 4 inches  
**Length:** 65 feet, 11 inches  
**Height:** 12 feet, 5 inches  
**Maximum Speed:** High subsonic  
**Maximum Takeoff Weight:** 52,500 pounds  
**Ceiling:** 45,000 feet  
**Range:** Unlimited with aerial refueling  
**Crew:** One  
**Armament:** Up to 4,000 pounds of internal stores  
**Date Deployed:** 1982  
**Retired:** 2008



A model of a F-117 Stealth Fighter variant underwent development testing in 16T.



Models of the BLU-109 JDAM weapon and F-117 aircraft are inspected in 4T.

awarded to Lockheed. The aircraft's first flight was in 1981 – only 31 months later – thanks largely to streamlined management by Aeronautical Systems Division, Wright-Patterson, Air Force Base (AFB), Ohio.

The F-117A can employ a variety of weapons and is equipped with sophisticated navigation and attack systems integrated into a state-of-the-art digital avionics suite that increases mission effectiveness and reduces pilot workload.

In 1994, the F-117 underwent developmental testing at AEDC in the center's 16-foot transonic wind tunnel (16T).

In 1998, with a goal to obtain Mk-84 and Bomb Live Unit (BLU)-109 Joint Direct Attack Munitions (JDAM) weapons certification for the F-117A, a weapons separation test was conducted in the 4-foot transonic wind tunnel (4T). The Mk-84 is a 2,000-pound, high-explosive, freefall munition used as a first-choice weapon for many missions and "high priority" targets. The BLU-109, an improved 2,000 pound-class bomb, is a penetrator weapon with a much harder skin than the Mk-84. The skin is a single-piece, one-inch high-grade steel, forged warhead casing.

In Desert Storm, the BLU-109 was coupled with a laser

guidance kit to form a laser-guided bomb.

AEDC manufactured 5-percent scale models of the munitions to observe their separation characteristics from the aircraft model supplied by the customer.

Data taken included freestream, aerodynamic grid and captive trajectory data at Mach numbers ranging from 0.60 to 0.90. Store free-stream data were obtained with the aircraft model removed from the test section.

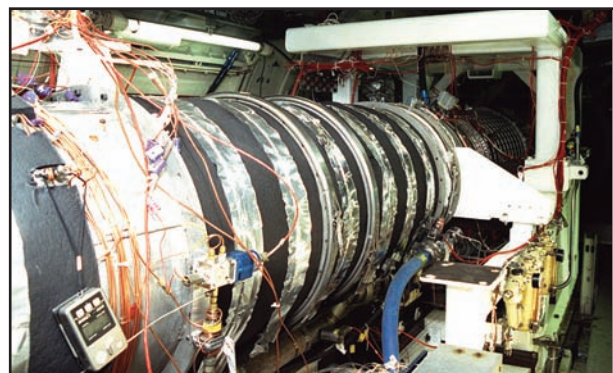
Aerodynamic grid data were gathered by commanding the Captive Trajectory System (CTS) to drive the store model to a series of preselected positions relative to the aircraft model. (The CTS is a computer-controlled, six-degrees-of-freedom model-positioning system that permits tracing the trajectory of a missile, bomb or any other external store with respect to the aircraft to simulate events accompanying weapons release.)

Test parameters included varying angles of attack, aircraft sideslip angles and a simulated altitude of 20,000 feet. Installation and testing were completed in one week with AEDC engineers accomplishing more than 100 percent of the customer's objectives.

In addition to wind tunnel and weapon separation testing, AEDC also conducted altitude testing on the F-117's power plant.

Operation Desert Storm first saw the potential of an aircraft that could penetrate dense threat environments at night. Comprising 2 to 3 percent of coalition air forces, the F-117 accounted for 30 to 35 percent of first-night targets attached with hit rates of 75 percent in Desert Storm to more than 90 percent in Operation Allied Force.

The F-117 also sustained the highest mission-capability rates of any deployed fighter or bomber in both conflicts, exceeding 82 percent.



Above, the F404-GE-102, the power plant for the aircraft, awaits testing in AEDC's test cell T-4.

# A-10

## Thunderbolt II

*The A/OA-10 Thunderbolt II is the first Air Force aircraft specially designed for close air support of ground forces. This highly maneuverable aircraft can be used against all ground targets, including tanks and other armored vehicles. The plane's wide combat radius and short takeoff and landing capability permit operations in and out of locations near front lines.*

### Characteristics

**Primary Function:** Close air support (A-10); airborne forward air control (OA-10)

**Contractor:** Fairchild Republic

**Power Plant:** Two GE TF34-GE-100s

**Thrust:** 9,065 pounds per engine

**Wing Span:** 57 feet, 6 inches

**Length:** 53 feet, 4 inches

**Height:** 14 feet, 8 inches

**Maximum Speed:** 420 miles per hour

**Maximum Takeoff Weight:** 51,000 pounds

**Ceiling:** 45,000 feet

**Range:** 800 miles

**Crew:** One

**Armament:** One 30-mm GAU-8/A seven-barrel Gatling gun; up to 16,000 pounds of mixed ordnance on eight under-wing and three under-fuselage pylon stations, including 500-pound Mk-82 and 2,000 pounds Mk-84 series munitions, AGM-65 Maverick missiles and laser-guided/electro-optically guided bombs; infrared countermeasure flares; electronic countermeasure chaff; jammer pods; 2.75-inch rockets; illumination flares and AIM-9 Sidewinder missiles

**Date Deployed:** October 1975

**Inventory:** Active force: A-10, 143; OA-10, 70; Reserve, A-10, 46; OA-10, 6; ANG, A-10, 84; OA-10, 18



### Highlights of Development Testing at AEDC

- Preliminary store separation testing of two A-10 prototypes to help determine the best entry for the Air Force
- Exploratory testing of the General Electric (GE) TF34-GE-100 turbofan jet engine and the Avco Lycoming ALP502, the two potential power sources for the A-10
- Testing of a number of the aircraft's systems and munitions which helped the Air Force to determine the best ones to incorporate into the overall A-10 program

All three of the center's main facilities were involved in supporting the Air Force's new close air support aircraft during 1973. The Engine Test Facility (ETF) concluded its T-1 test cell trials of the F102 engine for the unsuccessful Northrop entry in the competition as the year began. Fairchild Industries' A-10 was selected as winner of the contract after flight evaluation, and testing of its TF34 engine began in test cell J-1.

The von Kármán Gas Dynamics Facility's (VKF) connection with the program came through G-Range, which was involved with tests of the 30-mm cannon the aircraft was scheduled to carry. The tests were part of a "shoot-off" between Philco-Ford and General Electric (GE), with GE being selected in June as the gun contractor.

Later tests in G-Range were run on ammunition proposed for use in the GAU-8 gun system. The Propulsion Wind Tunnel facility (PWT) contributed to development of the aircraft through an extensive series of payload tests, matching a model of the A-10 with a wide range of stores.

AEDC conducted preliminary store separation testing on the two A-10 prototypes to help determine the best entry for the Air Force. The center also performed exploratory testing of the GE TF34-GE-100 turbofan jet engine and the Avco Lycoming ALF 502, the two potential power sources for the A-10. AEDC's testing of a number of the aircraft's systems and munitions helped the Air Force to determine the best ones to incorporate into the overall A-10 program.

Five-percent scale models of the Fairchild-Republic A-10 close support aircraft and several types of stores were used in wind tunnel tests beginning on Jan. 31, 1974. These tests, sponsored by Air Force Systems Command's (AFSC) Aeronautical Systems Division (ASD), were to determine if the different stores would separate cleanly when dropped or launched at various flight speeds (220 to 380 mph). Aerodynamic



Left, A-10 stores are prepared for testing and evaluation in 4T. Right, one of the first jet engines at AEDC to be studied with the short-duration engine testing technique developed was the TF34. The engine was tested both with the traditional steady-state techniques, in which the engine operating conditions are set at some discrete point before measurements are made, and with the short-duration techniques, in which measurements are made as the engine undergoes controlled changes in operation.

forces were measured as the stores, mounted on the upper support system, were separated at varying distances from the aircraft. The equivalent of 98 separate trajectories were calculated during the nine-day test. About half of the test time was used to study local flow disturbances under the aircraft, near the wing pylons to which these stores are attached.

In April 1974, a series of developmental tests of the 30-mm ammunition to be used with the new A-10 close air support aircraft were completed at AEDC. A total of 43 shots was made in the center's 1,000-foot underground ballistic range using five different designs from Aerojet-General Corporation, subcontractor to GE for ammunition for the GAU-8 gun systems.

The tests, all at ambient atmospheric pressure, were conducted to examine the projectiles' aerodynamic, stability and drag characteristics. Results were to be compared with earlier tests to determine the effect of design refinements and modifications made since the competitive "shoot off" a year earlier. The rounds were fired singly through a barrel supplied by GE.

This was the third test series in connection with the GAU-8 system. The first series, in August and September of 1972, provided the contending teams – GE Aerojet and Philco-Ford/Honeywell – an opportunity to test their preliminary designs. For the first three months of 1973, the AEDC range was used as part of the evaluation process that led to selection of the GE/Aerojet team in June.

In addition to testing the aerodynamics of the A-10, AEDC also performed exploratory testing of the TF34-GE-100 turbofan jet engine, power plant for the A-10 close air support aircraft. The tests, completed in September 1974, covered much of the aircraft's speed range.

By 1975, the GE TF34-GE-100 turbofan had undergone testing through much of the previous year in the J-1 test cell. Other tests related to the aircraft included a series on



Aerodynamic evaluation of the 30-mm ammunition for use in the GAU-8 rapid fire cannon for the A-10 close air support aircraft, which was completed in the center's 1,000-foot underground ballistic range, was part of the evaluation process that resulted in the selection of GE to continue with full-scale development of the GAU-8. Below, this 5-percent scale model of the Fairchild-Republic A-10 Thunderbolt, a single-seat close air-support aircraft, was used to conduct store separation tests in 4T.



the 30-mm ammunition for the A-10's GAU-8 gun system that began aerial tests in early 1974 at Edwards Air Force Base (AFB), where the aircraft also had been undergoing flight tests.

By mid-year, dual-purpose and tunnel tests matching the A-10 close air support aircraft and the television-guided Maverick air-to-ground missile were completed. The purpose of the tests was to determine the effects of the air flowing around the parent aircraft on the missile's stability and to measure captive loads on the missile on an under-wing pylon. The tests were the third in support of the A-10 program to be done in 4T in more than four years.

# F/A-18

## Hornet

*The U.S. Navy's F/A-18 Hornet was the nation's first designated strike-fighter and was designed for traditional strike applications without compromising its fighter capabilities. All F/A-18s can be configured quickly to perform either fighter or attack roles through selected use of external equipment to accomplish specific missions, giving an operational commander more flexibility in employing tactical aircraft in a rapidly changing battle scenario.*



### Characteristics

**Primary Function:** Multi-role attack and fighter aircraft

**Contractor:** McDonnell Douglas

**Power Plant:** Two F404-GE-402

**Thrust:** 17,700 pounds per engine

**Wing Span:** 40 feet, 5 inches

**Length:** 56 feet

**Height:** 15 feet, 4 inches

**Maximum Speed:** Mach 1.7+

**Maximum Takeoff Weight:** 51,900 pounds

**Ceiling:** 50,000+ feet

**Range:** Combat: 1,089 nautical miles, clean plus two AIM-9s

**Ferry:** 1,546 nautical miles

**Crew:** A/C: One; B/D: Two

**Armament:** One M61A1/A2 Vulcan 20-mm cannon; AIM 9 Sidewinder, AIM 7 Sparrow, AIM-120 AMRAAM, Harpoon, Harm, SLAM, SLAM-ER, Maverick missiles; JSOW; JDAM

**Date Deployed:** November 1978; Operational October 1983 (A/B); September 1987 (C/D)

**Inventory:** 1,458

### Highlights of Development Testing at AEDC

- **Aerodynamic loads and store separation testing on the F/A-18 Hornet and F404-GE-400 engine and the aircraft's associated payloads**
- **Testing of stores including GBU-10, GBU-24 B/B, Joint Standoff Weapon (JSOW), Joint Direct Attack Munition (JDAM), Standoff Land Attack Missile-Extended Range, Mk-84 LD, Mk-83 LD, Mk-20, Mk-82 BSU86, AGM-88, AGM-65 and a 480-gallon fuel tank**
- **Used Computation Fluid Dynamics (CFD) methodology to validate data collected from wind tunnel testing at AEDC and other ground test facilities**
- **Studies of bird impact on the aircraft's canopy at the center's Bird Strike Impact Range**

AEDC performed propulsion tests in the 1970s on the YF-17's prototype engines - the General Electric (GE) YJ101, twin-spool augmented turbofan in the 15,000-pound class. AEDC engineers performed drag and stability tests of the YF-17 in 16T. Tests using an 8-percent scale model determined aerodynamic characteristics at a variety of yaw angles and angles of attack throughout the transonic speed range. AEDC explored the effects of several proposed changes on the overall drag of the aircraft.

In 1976, AEDC tested a large-scale model of the YF-17, minus tail and outboard wing sections. Movable conical plugs controlled airflow through the model's engine inlets by restricting the exit. A small pressure rake in front of the inlet provided data on the airflow going into the inlet.

In March 1977, the first aerodynamic tests of the F/A-18 at AEDC evaluated the effects of minor changes in the airframe and fixed air inlets on the stability and performance of the inlets.

In addition, the center has used Computational Fluid Dynamics (CFD) methodology to validate data collected from April 1977.

Extensive wind tunnel tests that examined the flight characteristics of the F/A-18 fighter were completed.

In the 30 years that has followed that test, AEDC also conducted



aerodynamic loads and store separation testing on the F/A-18 Hornet and F404-GE-400 engine and the aircraft's associated payload, including the GBU-10, GBU-24 B/B, Joint Standoff Weapon (JSOW), Joint Direct Attack Munition (JDAM), Standoff Land Attack Missile-Extended Range, Mk-84 LD, Mk-83 LD, Mk-20, Mk-82 BSU86, AGM-88, AGM-65 and a 480-gallon fuel tank.

In the first phase of the tests, drag measurements were made at simulated flight speeds from about 450 to more than 1,100 miles an hour (Mach 0.6 to 1.55). Included were the drag effects created by the external carriage of Sidewinder and Sparrow missiles, Mk-85 munitions and a 300-gallon auxiliary fuel tank. The remainder of the program was concerned with

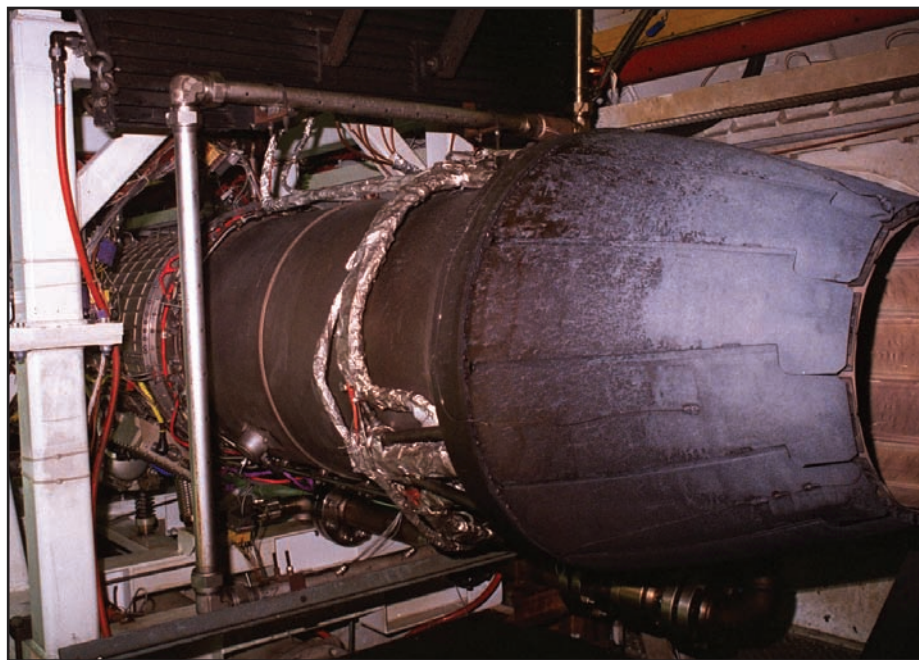


**Extensive wind tunnel tests have examined the flight characteristics of the Navy's F/A-18 fighter. In the first phase of the tests, drag measurements were made at simulated flight speeds from Mach 0.6 to 1.55.**

the aircraft's stability and control characteristics over the same speed range at a wide range of attack and yaw angles.

In November 1977, AEDC personnel completed a highly detailed study in the center's 16-foot transonic wind tunnel (16T) of the stability and performance of the inlets that direct air to the engines of the Hornet. Simulated flight speeds ranged from zero to more than 1,000 miles an hour over a number of angles of attack and sideslip. Nearly 350 sensors were installed in the model to record air pressures. The studies were a continuation of inlet performance tests conducted in both 16T and the 16-foot supersonic (16S) wind tunnels at AEDC late in 1976.

In the late 1970s, the center's 4-foot transonic wind tunnel (4T) was the site of extensive aerodynamic tests examining the



**General Electric's (GE) first F404-GE-402 engine to be tested at AEDC underwent 70 hours of testing in T-2 in 1996. Previously, the F404 was tested exclusively at the Naval Air Warfare Center at Trenton, New Jersey. When that facility was closed, the test program transferred to AEDC.**



An AEDC engineer checks out a scale model High-speed Anti-Radiation Missile (HARM) attached to a Navy F/A-18 model before the start of a test in 4T. The tests helped ensure that missiles and other stores would safely separate from the aircraft during actual flight.

compatibility of the Hornet and the AIM-7F Sparrow air-to-air missile. A model of the missile was separated from the aircraft and a computer recorded aerodynamic forces on the missile to help analysts determine if the separation would be clean in flight.

In June 1978, AEDC conducted a series of tests that examined the compatibility of the Hornet with various externally carried payloads. The first F/A-18 payload separation test used the center's computer-controlled support system and tested the Hornet in combination with the AIM-7F Sparrow air-to-air missile. In the last series, externally carried payloads studied in addition to the Sparrow were the Mk-82 Snakeye bomb, the 300-gallon auxiliary fuel tank and the AIM-9 Sidewinder missile.

In 1990, the F/A-18 returned to the center's tunnels so that AEDC engineers could determine whether the High-speed Anti-Radiation Missile (HARM) would safely separate from the aircraft.

The first General Electric (GE) F404-GE-402 engine to be tested at AEDC was installed in propulsion development test cell T-2 in 1996.

The F404-GE-400 underwent a short test period of about 70 air-on hours spanning an eight-week period. Previously, the F404, which has been in production for 16 years, was tested exclusively at the Naval Air Warfare Center at Trenton, New Jersey. However, as a result of the Base Realignment and Closure Commission,

(BRAC) the Trenton facility was closed and testing was transferred to AEDC.

The purpose of the test was two-fold – to demonstrate that AEDC was capable of testing the F404 and, since it was a component improvement program test, to evaluate the performance improvements of the afterburner flame-holder.

In the fall of 1995, AEDC put the F/A-18 to the “bird strike” test. Collisions between aircraft and birds cause damage to thousands of aircraft and occasionally result in loss of life. Higher speeds and lower operating altitudes have compounded the problem. However, in recent years steps have been taken to at least lessen the damage caused by the midair collisions of birds and aircraft.

Manufacturers of military aircraft must now meet certain aircraft windshield durability requirements before their aircraft is accepted by a particular service.

AEDC's bird impact range is dedicated to testing the design and development of lightweight, optically suitable windshields and canopies that can withstand high impact forces without breaking, shattering or excessive bending.

Chicken carcasses traveling up to 490 mph strike an aircraft after being launched from an air-powered Navy



AEDC completed a highly detailed study of the stability and performance of the inlets that provide air to the engines of the F/A-18 fighter. Simulated flight speeds ranged from zero to more than 1,000 miles an hour over a number of angles of attack and sideslip. Nearly 350 sensors were installed in the model to record air pressures. The studies were a continuation of inlet performance tests conducted earlier in both the 16-foot transonic and supersonic wind tunnels in 1977.

gun barrel obtained in 1972.

As is often the case, some damage occurred to the windshield, but since it was a ground test using nothing but the aircraft fuselage and cockpit, no crew members were hurt, as is sometimes the case in actual bird and aircraft encounters.

During the F/A-18 tests, 4-pound chicken carcasses were fired at the cockpit windshields while high-speed motion picture photography (5,000 frames per second) was used to record the impact and deflection of the windshields.

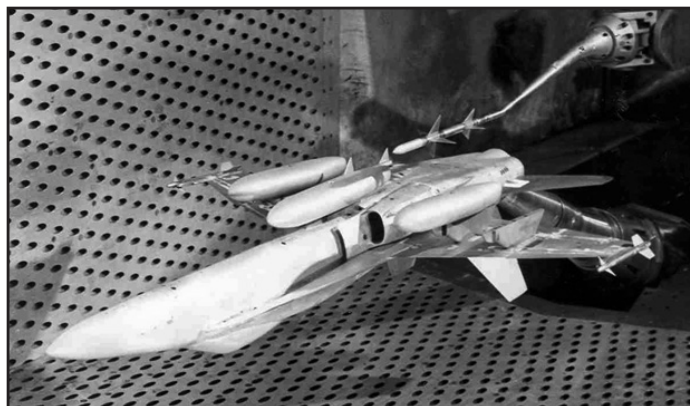
When the movie film was replayed at (24 frames per second), engineers were able to view the bird strike in slow motion and make deflection measurements of the transparency and support system.

AEDC performed weapons separation tests in 1999 to provide a flight test matrix for an upcoming Navy flight test of the F/A-18C/D Hornet fighter carrying and dropping the JDAM. The tests used 0.06-scale F/A-18C/D and JDAM-110 models in the 4T wind tunnel to investigate the aerodynamic and separation characteristics of the JDAM when dropped from the F/A-18. The JDAM-110 used in the certification process is the former Mk-83/BLU-110 1,000 pound general purpose bomb modified with a Boeing-produced JDAM kit. The low-cost guidance kit is used to convert existing Mk-83/BLU-110, Mk-84 and BLU-109 bombs into accurately guided "smart" weapons, using GPS signals for guidance.

Weapons certification is a five- to 15-month-long process designed to acquire and analyze wind tunnel data and use it to prepare a flight test plan/matrix for flight testing. During the test, air-to-air missile, external fuel tank and air-to-ground stores configuration loadouts were tested to capture the interference flow-field effects of neighboring stores on the JDAM at specified aircraft locations. Using the center's CTS mechanism, NAVAIR obtained JDAM store aerodynamic data in the freestream and in the presence of the aircraft model. Test conditions included Mach numbers from 0.80 to 1.30.



**Wind tunnel tests in 16S using the F/A-18 as a test vehicle investigated possible improvements in performance of jet fighters – improvements which may be gained by equipping an aircraft with rectangular jet nozzles instead of round ones.**



**A scale model of the Navy's F/A-18 Hornet jet fighter – equipped with various external payloads – was tested in 4T.**

In 2003, testing of the new General Electric (GE) F404-GE-402 engine with a new radial flameholder was successfully completed in the center's Propulsion Development Test Cell T-4. While at AEDC, the 17,700-pound thrust engine underwent approximately 51 hours of simulated altitude testing under a Navy Component Improvement Program (CIP) on behalf of the Finnish and Swiss air forces, international operators of the F/A-18 aircraft. The test objectives were to demonstrate performance, light-off capability and operability of the F404-GE-402 engine with the radial flamehold installed.

In the fall of 2003, a Navy F/A-18 Hornet became a static display aircraft at Arnold's Main Gate. It was later moved to Gate 2.

# C-141

## Starlifter

*The C-141B Starlifter was stretched from the C-141A version and given in-flight refueling capability. The C-141A was lengthened by 23 feet, 4 inches, which increased the cargo capability by about one third. Lengthening of the aircraft had the same effect on the fleet as increasing the number of aircraft by 30 percent. With the capability to deliver equipment, as well as airlift combat forces and resupply those forces, the C-141 Starlifter met critical requirements for mobility. Additionally, with the aerial refueling capability the C-141 Starlifter could transport the sick and wounded troops from a hostile area to advanced medical facilities far from the battlefield.*



### Highlights of Development Testing at AEDC

- Ensured safety and reliability of the aircraft through studies of two possible leading-edge contours along with the current leading-edge shape, with measurements taken with swept wingtips and various wing trailing-edge fairings attached

The feasibility of improving the aerodynamic performance of the C-141B Starlifter, then the Air Force's second largest transport – by reshaping the leading edge of its wing – was examined in wind tunnel tests in 1978.

Two possible leading-edge contours were studied along with the then-current leading-edge shape, and measurements were taken with swept



**A test technician checks out a seven-foot-span scale model in 16T in 1978. The tests were made to check the feasibility of improving aerodynamic performance of a stretched version with 23-foot longer fuselage.**

wingtips and various wing trailing-edge fairings attached. These were the first AEDC studies of the elongated Starlifter. A production contract was let on the C-141 fleet prior to the AEDC tests. Cargo bays were increased 23 feet in length by adding to both the fore and aft portions of the fuselage.

In 1995, AEDC conducted testing on the Pratt & Whitney (P&W) TF33 engine, which powered the C-141. The tests took place in the Aeropropulsion Systems Test Facility (ASTF) to baseline the engine's cold weather starting capability and range performance with JP-8 jet fuel. As a part of the worldwide fuel standardization effort, the jet fuel was converted from JP-4 to JP-8.

### Characteristics

**Primary Function:** Cargo and troop transport

**Contractor:** Lockheed

**Power Plant:** Four P&W TF-33-P-7 turbofan engines

**Thrust:** 20,250 pounds per engine

**Wing Span:** 160 feet

**Length:** 168 feet 4 inches

**Height:** 39 feet 3 inches

**Maximum Speed:** 567 miles per hour

**Maximum Takeoff Weight:** 342,100 pounds

**Ceiling:** 41,000 feet

**Range:** 2,935 miles

**Crew:** Five or Six

**Armament:** None

**Date Deployed:** C-141A: October

1964; C-141B: December 1979;

C-141C: October 1997

**Retired:** May 5, 2006

# F-14

## Tomcat

*The F-14 Tomcat was a supersonic, twin-engine, variable sweep wing, two-place strike fighter manufactured by Grumman Aircraft Corporation. The multiple tasks of navigation, target acquisition, electronic counter-measures and weapons employment were divided between the pilot and the radar intercept officer. Primary missions included precision strikes against ground targets, air superiority and fleet air defense. The F-14 Tomcat was officially retired on Sept. 22, 2006.*



### Highlights of Development Testing at AEDC

- **Store separation tests that helped NAVAIR determine the best placement for the F-14's weapons**
- **Extensive testing of the General Electric (GE) F110 engine in the center's test cells**

In April 1990, a model of the Navy's F-14 Tomcat aircraft, configured with the General Dynamics/Westinghouse concept for the Advanced Air-to-Air Missile (AAAM), underwent wind tunnel testing in the 4-foot transonic wind tunnel (4T) to ensure the structural integrity of the aircraft/missile match-up and reduce risks during the demonstration/validation phase.

At different times during testing, the aircraft was configured with the AAAM separation and control test vehicle, multiple launchers, an airborne track illuminator pod and a drop tank.

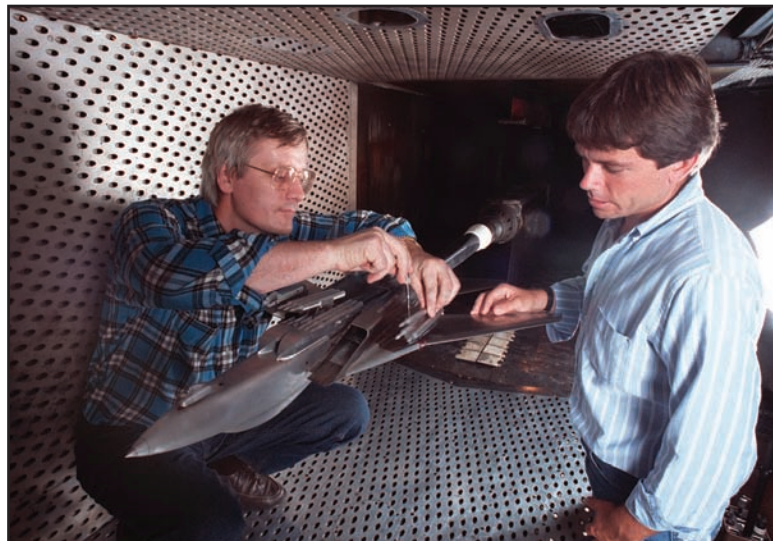
Using 1/20-scale models, engineers performed the series of tests that provided static stability, drag, carriage loads and separation data. A Captive Trajectory Systems (CTS) was used to obtain captive trajectory, aerodynamic grid and freestream data.

During the CTS testing phase, data were obtained at Mach numbers from 0.70 to 1.60.

The Tomcat's armament was occasionally updated to maintain pace

### Characteristics

**Primary Function:** Strike fighter  
**Contractor:** Northrop Grumman  
**Power Plant:** F-14A: (2) TF30-414A Afterburning Turbofans, F-14B/D: (2) F110-GE-400 Afterburning Turbofans  
**Thrust:** F-14A: more than 40,000 pounds per engine; F-14B/D: more than 54,000 pounds per engine  
**Wing Span:** 64 feet unswept; 38 feet swept  
**Length:** 62 feet, 9 inches  
**Height:** 16 feet  
**Maximum Speed:** Mach 2+  
**Maximum Takeoff Weight:** 43,600 pounds (F-14B)  
**Ceiling:** 50,000+ feet  
**Range:** 1,600 nautical miles  
**Crew:** Two  
**Armament:** Guns: one M61 Vulcan 20-mm Gatling Gun; AIM-54 Phoenix, AIM-7 Sparrow and AIM-9 Sidewinder air-to-air  
**Date Deployed:** September 1974  
**Retired:** September 2006



An F-14 Tomcat model is readied in 1990 for a store separation test in 4T.

## F-14 Tomcat

with new technology. In 1995, the Naval Air Systems Command (NAVAIR) asked AEDC to perform wind tunnel tests on the aircraft configured with an Air Intercept Missile (AIM)-7F Sparrow missile and a Guided Bomb Unit (GBU)-24 B/Bs (laser guided bombs).

The tests, using 5-percent scale models, took place in 4T. The first phase consisted of testing two GBU-24 B/Bs in two different configurations.

The Navy required the tests to determine if the weapons could be safely separated from the aircraft during flight. In particular, the Navy needed to know which configuration, if either, would allow GBU-24 B/Bs to separate safely.

On the basis of trajectory test data, technical representatives from NAVAIR decided on the best positioning of the stores. Subsequent aerodynamic grid and carriage loads data were acquired for this configuration. Airflow in the tunnel reached speeds ranging from Mach numbers 0.8 to 1.4. A second phase was added with two GBU-10 stores or one GBU-24 mounted on the forward stations, with an AIM-7F Sparrow missile tucked away in the aft centerline missile well.

Just as the center has subjected models of the F-14 to the rigors of wind tunnel testing, AEDC engineers thoroughly tested the F110 power plant for the fighter.

## F-14 static display dedicated to fallen Navy pilot

In March 2007, in observance of Women's History Month, base officials dedicated the F-14D Tomcat static display aircraft at the Main Gate in honor of a fallen female Navy aviator.

Lt. Kara Hultgreen, the Navy's first female carrier-based combat fighter pilot, was killed in a crash in October 1994 in the F-14 she was piloting.

Lieutenant Hultgreen was assigned to the Black

Lions of Fighter Squadron 213 aboard the aircraft carrier *USS Abraham Lincoln*. The F-14 dedicated in her honor had been assigned to the same squadron.

The unit was conducting training operations in preparation for deployment to the Persian Gulf when the crash occurred. The Tomcat she piloted experienced engine failure on final approach and crashed in the Pacific Ocean. Her crewman survived.

The guest speaker was retired Navy Capt. Rosemary Mariner, the first woman to command an operational fleet squadron. During her 24 years of military service, Captain Mariner logged more than 3,500 military flight hours in 15 different naval aircraft and made 17 carrier landings.

Lieutenant Hultgreen is buried in Arlington National Cemetery.



Lt. Kara Hultgreen



Retired Navy Capt. Rosemary Mariner, the first woman to command an operational fleet squadron, spoke at the F-14 Tomcat Dedication Ceremony in honor of the late Lt. Kara Hultgreen.

# AV-8B

## Harrier

*The AV-8B Harrier II is a single-seat, light attack aircraft that provides offensive air support for the Marine Corps. By virtue of its vertical/short take-off and landing capability, the AV-8B can operate from a variety of amphibious ships, rapidly constructed expeditionary airfields, forward sites and damaged conventional airfields. The AV-8B is capable of attacking and destroying surface targets under day and night-time visual conditions.*

### Characteristics

**Primary Function:** Attack, destroy surface targets in day and night visual conditions

**Contractor:** McDonnell Douglas

**Power Plant:** One Rolls-Royce Pegasus F402-RR-408 vectored thrust turbofan engine

**Thrust:** 23,400 pounds

**Wing Span:** 30 feet, 3 inches

**Length:** 46 feet, 3 inches

**Height:** 11 feet, 7 inches

**Maximum Speed:** 630 mph

**Ceiling:** 38,000 feet

**Ferry Range:** 1,700 nautical miles

**Crew:** One

**Armament:** Mk-82 series 500-lb bombs, Mk-83 series 1,000-lb bombs, GBU-12 500-lb laser-guided bombs, GBU-16 1000-lb laser-guided bombs, AGM-65F IR Maverick missiles, AGM-65E Laser Maverick missiles, CBU-99 cluster munitions, AIM-9M sidewinders, Lightning II targeting POD to deliver GBU-12 and GBU-16.

**Date Deployed:** Jan. 12, 1985, AV-8BII (Plus) June 1993

**Inventory:** 7 squadrons with 16 aircraft each; 1 training squadron



### Highlights of Development Testing at AEDC

- Conducted store separation testing
- Assessed the performance of the Rolls-Royce Pegasus vectored thrust engine in two facilities

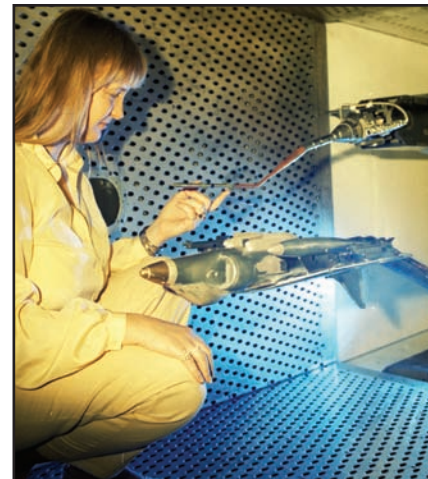
Designed to attack and destroy surface targets under day and night visual conditions, the AV-8B Harrier serves as the replacement for the AV-8A and the A-4M light attack aircraft. A vertical/short takeoff and landing (V/STOL) strike aircraft, the Harrier is powered by one Rolls-Royce F402-RR-408 turbofan engine.

The Marine Corps requirement for a V/STOL light attack force has been documented since the late 1950s. Combining tactical mobility, responsiveness, reduced operating cost and basing flexibility, both afloat and ashore, V/STOL aircraft are particularly well-suited

to the special combat and expeditionary requirements of the Marine Corps.

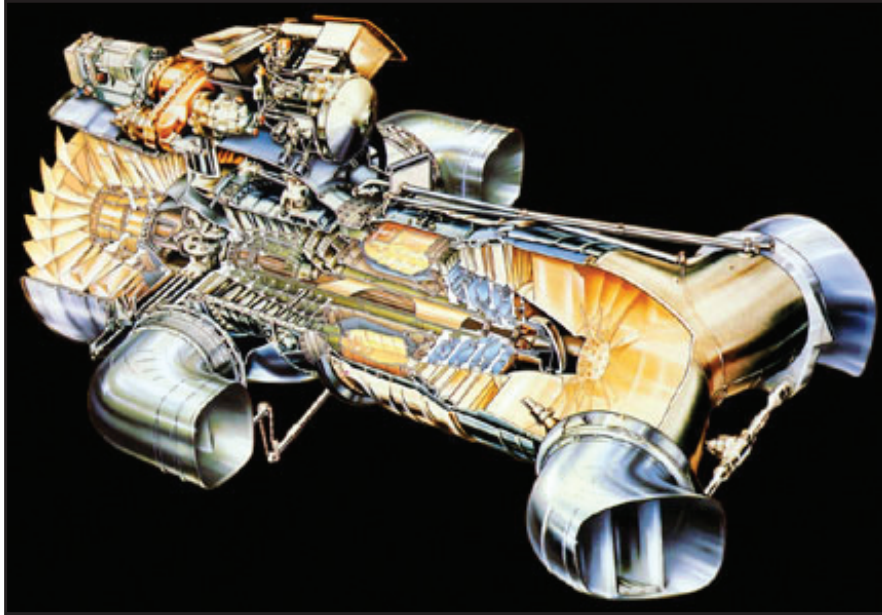
In 1981, the Marine Corps Harrier jump jet underwent store separation testing in the 4-foot transonic wind tunnel (4T).

Operation Desert Storm in 1991 was highlighted by expeditionary air operations performed by the AV-8B. The Harrier was the first Marine Corps tactical strike platform to arrive in theater and subsequently operated from various basing postures. Three squadrons, totaling 60 aircraft, plus one six-aircraft detachment operated ashore from an expeditionary airfield, while one squadron of 20 aircraft operated from a sea platform. During the ground war, AV-8Bs were based as close as 35 nautical miles from the Kuwait border, making them the most forward deployed tactical strike aircraft in

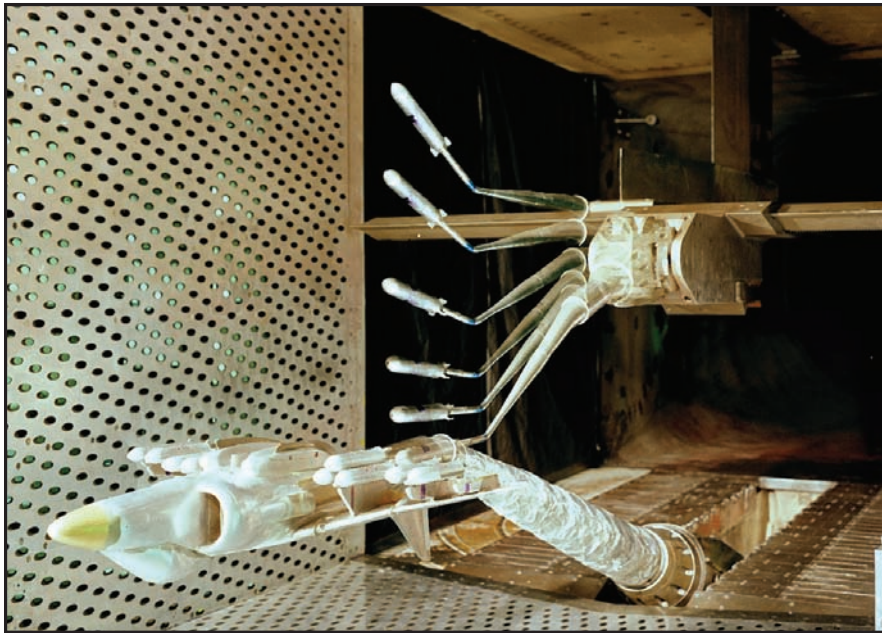


An AEDC project engineer looks over an AV-8B Harrier II aircraft before a wind tunnel test. The aircraft, mounted upside down for accessibility, underwent store separation testing with missile and bomb models. Attached to a captive trajectory support in this particular configuration is an AMRAAM missile.

## AV-8B Harrier



The F402-RR-408 Pegasus, the power plant for the AV-8B Harrier II and the second Rolls-Royce engine to be tested at AEDC, underwent approximately 72 air-on hours of altitude performance testing in test cell J-1. The objectives of the test were to assess the engine's altitude performance and to demonstrate AEDC's capabilities in handling this unique vectored-thrust engine.



Marine Corps Harrier Jump Jet stores separation tests were run in 1981.

theater. The AV-8B flew 3,380 sorties for a total of 4,083 flight hours while maintaining a mission capable rate in excess of 90 percent. Average turnaround time during the ground war surge flight operations was 23 minutes.

In 1996, the F402-RR-408 Pegasus, the power plant for the AV-8B Harrier II, underwent approximately 72 air-on hours of altitude performance testing in test cell J-1. The objectives of the test were to assess the engine's

altitude performance and to demonstrate AEDC's capabilities in handling this unique vectored-thrust engine.

The Harrier incorporates an innovative swiveling engine exhaust nozzle design with a lightweight airframe to permit unique maneuvering capabilities unmatched by conventional aircraft.

The Pegasus provides the Harrier II with both lift and propulsive thrust through four swiveling exhaust nozzles, which vector engine thrust from horizontal, for conventional flight, to vertical, for landing.

Previously, the F402, which had been in production in various versions for 25 years and has 21,500 pounds of thrust, had been tested in the United States exclusively at the Naval Air Warfare Center at Trenton, New Jersey. However, as a result of Base Realignment and Closure Commission (BRAC) decisions, the Trenton facility was closed, and testing was transferred to AEDC.

While the engine was being tested, a model of the Harrier underwent bomb and missile separation testing.

Characteristics of a Joint Direct Attack Munition (JDAM) and Advanced Medium Range Air-to-Air Missiles (AMRAAM) separating from an AV-8B Harrier II aircraft were determined during a wind tunnel test at the center.

Five-percent scale models of the weapons and aircraft were used during the test in wind tunnel 4T. The bombs and missiles were attached to a captive trajectory support, which moved them away from the host aircraft at specified intervals.

During the test, boundary-layer trips were used on the AV-8B leading edges to ensure a turbulent boundary layer, which is similar to what the actual plane would experience in flight. Twenty-one different configurations of the aircraft, bombs and missiles were tested.



# C-17

## Globemaster III



*The C-17 Globemaster III is an advanced cargo aircraft capable of rapid strategic delivery of troops and all types of cargo to main operating bases or directly to forward bases in the deployment area. The C-17 can carry virtually all of the Army's air-transportable equipment – military vehicles or pallet-sized cargo.*

*The design of the aircraft allows it to operate through small, austere airfields. The C-17 can take off and land on runways as short as 3,500 feet and only 90 feet wide. Even on such narrow runways, the C-17 can turn around using a three-point star turn and its backing capability.*

### Characteristics

**Primary Function:** Cargo and troop transport  
**Contractor:** Boeing  
**Power Plant:** Four P&W F117-PW-100 turbofan engines  
**Thrust:** 40,440 pounds per engine  
**Wing Span:** 169 feet, 10 inches  
**Length:** 174 feet  
**Height:** 55 feet, 1 inch  
**Maximum Speed:** Mach 0.76  
**Maximum Takeoff Weight:** 585,000 pounds  
**Ceiling:** 45,000 feet at cruising speed  
**Range:** Global with in-flight refueling  
**Crew:** Three  
**Armament:** None  
**Date Deployed:** June 1993  
**Inventory:** Active duty: 158; ANG: 8; Reserve: 8

### Highlights of Development Testing at AEDC

- **Highly productive aerodynamic loads testing**

When Douglas Aircraft brought a 5.8-percent scale model of the C-17 cargo aircraft to AEDC for testing in 1983, they expected to get only 70 percent of the data they needed and that a second test period would be required.



**A highly instrumented C-17 model, with 15 remote-controlled surfaces was tested in 16T in 1983.**

Actually 100 percent of the data required were collected during the first

test entry. This was only one of the productivity records that were set during a four-week test in the 16-foot transonic wind tunnel (16T). Planning had begun more than a year earlier, when the customer told AEDC what they wanted, and the program was one of the most productive and well-planned tests conducted at the center.

Douglas had designed and built a highly articulated scale model of the C-17 that weighed about a ton with 1,550 pressure measurement ports. At the time, it was the most sophisticated model ever tested at AEDC.

Low-speed wind tunnel testing had been done elsewhere to validate the design. AEDC testing provided information on the high-speed aerodynamic performance and structural integrity of the design and established a database for the full-scale engineering development phase.

Normally test engineers spend half the time taking data and half making manual changes to the model's control surfaces. However, this model was built with 15 remote-controlled surfaces that allowed changes in aircraft configuration without interrupting the tunnel's airflow. As a result, data gathering accounted for about 75 percent of the test time – a significant increase. More than 30 million measurements were gathered during the test.

Another feature that promoted increased productivity was the introduction of a new Electronically Scanned Pressure (ESP) measuring system. Thirty-two ESP modules were installed inside the C-17 model. The ESP system modules allowed engineers to simultaneously scan 1,100-plus ports and saved the program about \$1 million in tunnel test time.

# V-22

## Osprey

As effective as a conventional helicopter with its vertical take-off and landing (VTOL) capability, the V-22 Osprey also has the long-range cruise and higher speed of a twin turboprop aircraft.

The Osprey is the world's first production tiltrotor aircraft with a 38-foot rotor system and engine/transmission nacelle mounted on each wingtip. While it can operate as a helicopter when taking off and landing vertically, once airborne, the nacelles rotate forward 90 degrees for horizontal flight, converting the V-22 to a high-speed, fuel-efficient turboprop airplane.

The wing also rotates for compact storage aboard ship. The first flight occurred in March 1989; in September 2005, the Pentagon formally approved full-rate production for the V-22.

### Characteristics

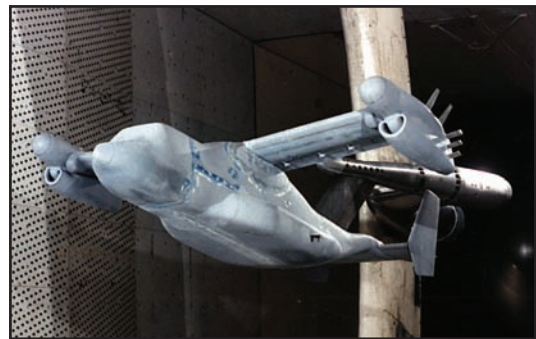
**Primary Function:** VTOL aircraft  
**Contractor:** Bell-Boeing  
**Power Plant:** Two pivoting Rolls-Royce/Allison AE1107C engines  
**Thrust:** More than 6,200 shaft horsepower per engine  
**Wing Span:** 84 feet, 7 inches  
**Length:** 57 feet, 4 inches  
**Height:** 22 feet, 1 inch  
**Maximum Speed:** 277 miles per hour  
**Maximum Takeoff Weight:** 52,870 pounds  
**Ceiling:** 25,000 feet  
**Range:** 2,100 nautical miles with internal auxiliary fuel tanks  
**Crew:** Four  
**Armament:** None  
**Date Deployed:** IOC 2009  
**Inventory:** 3



### Highlights of Development Testing at AEDC

- Testing on the V-22 Osprey using for the first time, the High-Angled Automated Sting (HAAS) model support system, as well as Computational Fluid Dynamic (CFD) calculations

In 1985, the Navy became AEDC's first customer to use the double roll capability of the new High-Angle Automated Sting (HAAS) model-support system in the 16-foot transonic wind tunnel 16T.



The Navy's V-22 Tilt Rotor was the first model tested with the HAAS in 16T.

A 15-percent scale model of the Bell-Boeing JVX

Tilt Rotor, which was then under development by the user and renamed the V-22 Osprey, underwent testing to gather data on the high-speed aerodynamic performance of the design and to establish a base for further evaluation.

The new computer-controlled HAAS made welcome contributions to testing capabilities in 16T by increasing model attitude ranges by 50 percent and angular positioning speed by 200 percent for a significant increase in data productivity.

In testing the V-22 Tilt Rotor, for example, the new support system capability allowed AEDC to meet the user's requirement to maintain the model's lift center at the same point in the test section during pitch and yaw angle variation and to maintain wings level during yaw angle variation.

In addition to obtaining the test data, AEDC engineers made computational fluid dynamic calculations of the effects of the wind tunnel walls on the model V-22 data measurements. These calculations were made not only for 16T, but also for the Boeing 20-by-20-foot low-speed tunnel and the Boeing 8-by-12-foot tunnel, where the model was also tested.

At the same time, computations were also done to determine the interference effects of the new HAAS system on the model data.

# F-22A

## Raptor

*The F-22A Raptor, designed to replace the F-15 Eagle, is capable of performing both air-to-air and air-to-ground missions, combining stealth, supercruise, maneuverability and integrated avionics to make it a key component of the 21st century Air Force.*

*The aircraft is designed to project air dominance and provide a rapid and long-range strike capability to defeat threats.*

*The Raptor program motto has been "first look, first shot, first kill."*



### Highlights of Development Testing at AEDC

- **Extensive involvement with the F-22A Raptor beginning in the late 1980s with aerodynamic testing on the two competing aircraft/airframes and two associated engine prototypes for the Air Force's next generation fighter which will replace the F-15 Eagle**
- **Choice in 1991 of the Lockheed Martin YF-22 aircraft and the YF119 Pratt & Whitney engine to fulfill the air dominance vision**
- **Comprehensive engine, inlet and store separation testing that followed first flight continues at AEDC**

### Characteristics

**Primary Function:** Air dominance, multi-role fighter

**Contractor:** Lockheed-Martin,

**Power Plant:** Two F119-PW-100 turbofan engines

**Thrust:** 35,000 pounds per engine

**Wing Span:** 44 feet, 6 inches

**Length:** 62 feet, 1 inch

**Height:** 16 feet, 8 inches

**Maximum Speed:** Mach 2+

**Maximum Takeoff Weight:** 80,000 pounds

**Ceiling:** Above 50,000 feet

**Range:** more than 1,850 miles

**Crew:** One

**Armament:** One M61A2 20-mm cannon with 480 rounds; side weapon bays can carry two AIM-9 infrared air-to-air missiles, and main weapon bays can carry six AIM-120 radar-guided air-to-air missiles or two 1,000-pound GBU-32 JDAMs and two AIM-120 radar-guided air-to-air missiles

**Date Deployed:** December 2005

**Inventory:** Active force, 91

AEDC has played a key, behind-the-scenes role in delivering the first operational F-22A Raptor to Tyndall Air Force Base (AFB), Florida, Sept. 26, 2003.

Since the conception of the Advanced Tactical Fighter (ATF) program, AEDC turbine and aerodynamic testing has been instrumental in the development of the aircraft in its evolving forms.

The center became involved with the ATF program during the 54-month demonstration/validation program by testing its two prototypes. Lockheed teamed with General Dynamics and Boeing to develop the YF-22, and Northrop teamed with McDonnell Douglas to develop the YF-23. Both prototypes were source selection candidates.

In addition, General Electric (GE) and Pratt & Whitney (P&W) competed for the air tactical fighter engine contracts. The Lockheed Aircraft Company's YF-22 was selected to continue to the next stage, full-scale development, and P&W was selected to receive the initial contract for manufacturing engines.

Since 1989, AEDC has conducted more than 9,000 hours of engine testing, covering every phase of the engine's life cycle, including the Engineering and Manufacturing Development (EMD) Phase, Initial Service Release (ISR), Component Improvement Program (CIP) and Accelerated Mission Testing (AMT). AEDC has completed more than 3,500 air-on hours to support altitude assessment of the engine's performance, operability, aeromechanical and durability characteristics.

During the past 15 years, P&W's F119 engine has undergone testing

## F-22A Raptor



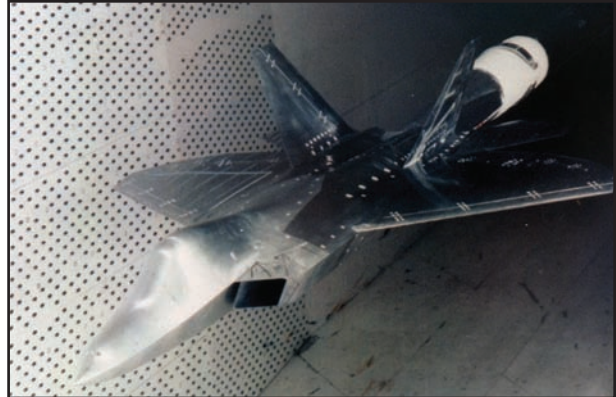
An F-22A aircraft model is maneuvered to a very high angle of attack during wind tunnel testing in 16T. This test helped to define performance and aircraft stability and control.

to evaluate the engine's aeromechanical performance, combustor and augmentor operability, vectored and nonvectored nozzle performance, fan performance, compressor stall margin and air start capability.

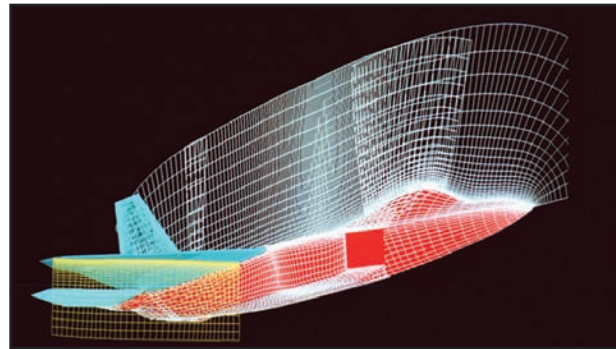
The F119 reached a milestone in 1997 with the completion of both an AMT and Preliminary Flight Qualification (PFQ) altitude performance test and an operability clearance test.

AEDC test crews used a highly instrumented P&W F119 engine as a developmental test bed in 2004. The engine, designated XTE67/SE1, was used to determine how well the computer simulations predicted high-cycle fatigue and engine stress points during flight. The Air Force Research Laboratory Propulsion Directorate and the F119 System Program Office sponsored the tests. During these tests, engineers provided near-real-time data on the engine's aeromechanical response using the Computer Assisted Dynamic Data Measurement and Acquisition System (CADDMAS), a significantly improved real-time data reduction system developed at AEDC, and the Non-intrusive Stress Measurement System (NSMS).

Test crews at AEDC have simulated nearly every



A model of the F-22A is prepared for testing in 16T. The F-22A is scheduled to replace the F-15 Eagle as the Air Force's front line fighter after the turn of the century. AEDC is involved in testing the F-22A propulsion system, aerodynamics and store separation configurations.



The F-22A Raptor undergoes CFD, a tool to complement wind tunnel tests and shorten the time needed to get complex information on aerodynamic effects.

flight condition the aircraft could expect to encounter in real-world missions. In the Aeropropulsion Systems Test Facility (ASTF) Test Cell C-2, altitude development tests subjected the engine to flight conditions the aircraft would experience during actual flight, providing the data P&W needed to prepare the engine for the CIP.

Since 2000, the engine completed testing required for the ISR setting a record when the team completed 65 air-on-hours of testing in only four days.

In 2001, the engine achieved 4,330 Total Accumulated Cycles (TAC) and underwent more than 1,037 engine-operating hours in the center's Altitude Test Cell C-1 and Sea Level Test Facility SL-2, meeting the Defense Acquisition Board's criteria for Initial Service Release (ISR). A TAC is a measure that takes the jet engine from one power setting to another then back to the original setting. The tests provided information on how the engine would perform after flying the 4,330 cycles. During those tests, the engine also set a new test pace record of 28 days while in C-1.

In 2002, AEDC began CIP testing to demonstrate the maturity of the design through accelerated maturation



AEDC engineers clean the window containing the sensor for an Advanced Infrared Search and Track system on an F-22A aircraft model. The aero-optical performance of the system was validated during wind tunnel testing at AEDC.



AEDC engineers used CFD to determine the flow fields around the F-22A. Here a fighter is shown carrying external fuel tanks.

testing and to examine engine sensitivity to expected variation in operation usage. The data acquired during those tests provided the manufacturer with information they sought for potential engine component improvements and established a baseline on how the engine will perform after flying a specified number of flight cycles representing six to eight years of in-service use.

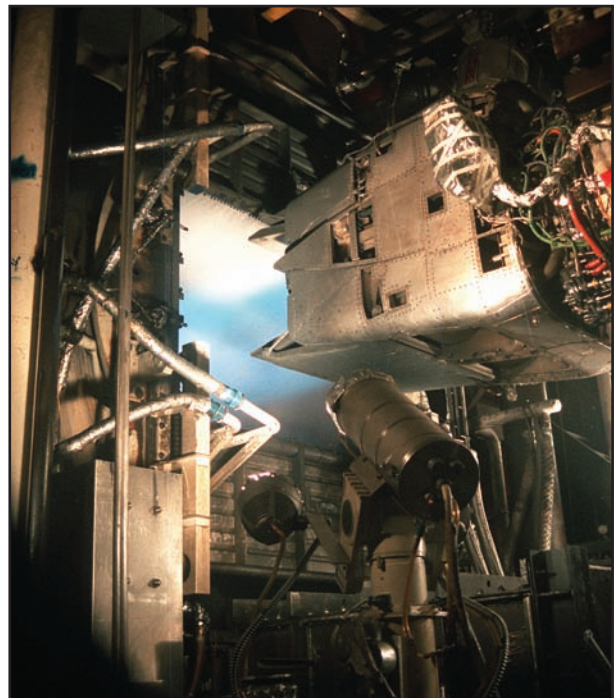
In addition to engine testing, the Raptor's airframe has also been extensively tested in AEDC's Propulsion Wind Tunnel Facility.

AEDC has performed about 50 percent of the engineering and manufacturing wind tunnel work on the F-22A. Center personnel performed approximately 8,000 user-occupancy hours of wind tunnel testing to help refine the shape and performance of the aircraft and verify safe weapons release in flight.

A wide variety of wind tunnel testing has been done at the center ranging from stability and control testing to aerodynamic drag testing to substantial weapons integration testing. Lockheed chief test pilot for the F-22A, Paul Metz, drove home the importance of the program, while praising AEDC's contribution when he visited



AEDC has conducted more than 9,000 hours of engine testing on the Pratt & Whitney F119 power plant for the F-22A Raptor.



The Pratt & Whitney YF119 prototype engine with a demonstrator nozzle was tested in ASTF in 1989.

## F-22A Raptor

the center. He compared the leap forward in technology being tested for the F-22A to the leap forward in bomber technology between World War II and today.

“Today, 20 B-2 bombers can do what hundreds of B-17s could do because of the leap forward in technological accuracy,” he said. “Today, from bombing altitude, we can put a bomb inside the cockpit of a plane on the ground. We don’t need the large numbers of bombs or aircraft when we can actually target the enemy directly. The F-22 presents us with that type of a leap forward, and with it we’ll be able to totally dominate every situation with smaller numbers of fighters.”

To support weapons integrations, the F-22A program and AEDC invested in a technology program to marry the most advanced technologies in wind tunnel testing, analysis methods and Computational Fluid Dynamics (CFD) to help certify safe separation of a wide range of stores from the F-22A.

The combination of these computational tools, test facilities and experienced analysts provided for an integrated analysis process best defined as Integrated Test and Evaluation (IT&E). The IT&E approach supports the F-22A program in several ways but especially in the area of safe store separation.

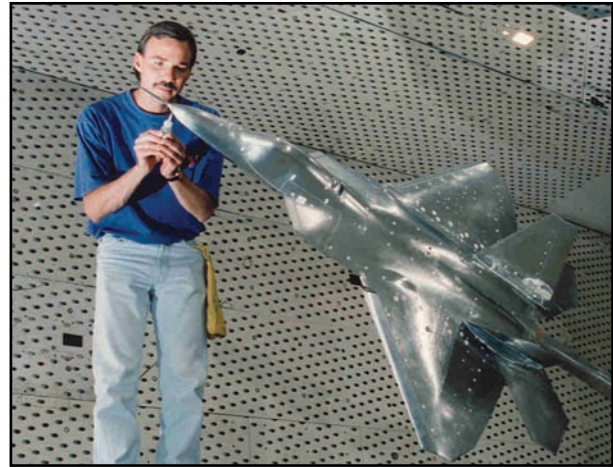
AEDC engineers supported the F-22 team effort to ensure safe separation of fuel tanks and weapons from the airframe in a variety of flight conditions. Using the IT&E approach, significant savings in test costs were realized and a greater understanding of the physics involved in the separation of stores from the F-22A was gained.

In 1992, an F-22A store separation team was established that consisted of personnel from what is now Lockheed Martin Aircraft Systems, the F-22A Systems Program Office, the Air Force SEEK EAGLE Office and AEDC. An ambitious IT&E plan was put in place to combine computations directly with wind tunnel test results to determine the separation characteristics of fuel tank/pylons, launched and jettison missiles, and jettisoned pylon/missile clusters.

The fuel tank/pylon jettison was of particular interest because in addition to the safe separation of the tank/pylon from the aircraft, there was a requirement to determine the reaction loads on the wing at the rear tank/pylon attachment point.

This required the development and modeling of the kinematic equations of motion for the restrained tank/pylon pivoting mechanism on the F-22A. A new innovative balance design that actually fit inside the contours of the pylon was also designed and fabricated at AEDC in order to perform captive trajectory testing of missile cluster jettisons in the wind tunnel.

Another challenge was the launch of missiles from the weapons bays. In addition to the launch of the missiles in normal flight, a study was conducted to investigate launch in



**An F-22A model is prepared for testing in AEDC's 16-foot transonic wind tunnel in 1993.**

a rolling pull-up maneuver. This required the development and modeling of arbitrary maneuvering aircraft kinematics combined with the standard computational simulations of separation already in use at AEDC to simulate missile launches from maneuvering aircraft.

The jettison of the tank/pylon from the wing using the constrained release was a very complex process to model. Thus, to provide confidence in the computations, there had to be a detailed validation process. To validate the computational methods, actual wind tunnel drops of dynamically scaled models (free-drop testing) were used to provide model-scale data for comparison with the computations.

Free-drop model tests are normally recorded on high-speed film by two orthogonal cameras operating at a rate of 400 frames per second. The analysis of this film provides reasonable position and orientation data for most applications, but the requirements for computational code validation require greater accuracy. Therefore, kinematic telemetry was developed to acquire linear and angular accelerations for several of the models jettisoned from the F-22A.

The integration of the telemetry packages within the 1/15th-scale 600-gallon fuel tanks required a cooperative effort between the team members. As the electronics package matured, the team members iterated on the placement of its various components within a stereo-lithography free-drop model using CAD/CAM equipment.

The free-drop model needed to match a set of required mass properties to properly emulate actual flight. The data were measured onboard the model and telemetered to a data acquisition system outside the wind tunnel.

The degree of correlation exhibited between the wind tunnel captive simulations, computational simulations and telemetry data for the tank-pylon dynamic drop validated the IT&E approach.

# F/A-18

## Super Hornet

*Compared to the original F/A-18A-D models, the Super Hornet – F/A-18E and F models – has longer range, an aerial refueling capability, increased survivability/lethality and improved carrier suitability. The E has a single seat while the F is a two-seater. The first operational cruise of the Super Hornet was with VFA-115 on board the USS Abraham Lincoln in 2002. The aircraft saw initial combat action in late 2002 in a strike on hostile targets in the “no-fly” zone in Iraq.*



### Highlights of Development Testing at AEDC

- **Aerodynamic loads and store separation testing on the F/A-18 Hornet, F414-GE-400 engine and the aircraft’s associated payloads**
- **Testing of stores including GBU-10, GBU-24 B/B, Joint Standoff Weapon (JSOW), Joint Direct Attack Munition (JDAM), Standoff Land Attack Missile-Extended Range, Mk-84 LD, Mk-83 LD, Mk-20, Mk-82 BSU86, AGM-88, AGM-65 and a 480-gallon fuel tank**
- **Use of Computation Fluid Dynamics (CFD) methodology to validate data collected from wind tunnel testing at AEDC and other ground test facilities**
- **Studies of bird impact on the aircraft’s canopy performed at the center’s Bird Strike Impact Range**

### Characteristics

**Primary Function:** Multi-role attack and fighter aircraft

**Contractor:** McDonnell Douglas

**Power Plant:** Two F414-GE-400

**Thrust:** 22,000 pounds per engine

**Wing Span:** 44.9 feet

**Length:** 60.3 feet

**Height:** 16 feet

**Maximum Speed:** Mach 1.8+

**Maximum Takeoff Weight:** 66,000 pounds

**Ceiling:** 50,000+ feet

**Range:** Combat: 1,275 nautical miles;

Ferry: 1,660 nautical miles

**Crew:** E: One; F: Two

**Armament:** One M61A1/A2 Vulcan 20-mm cannon; AIM 9 Sidewinder, AIM-9X (projected), AIM 7 Sparrow, AIM-120 AMRAAM, Harpoon, AGM-88 HARM, SLAM, SLAM-ER (projected), Maverick missiles; JSOW; JDAM; Data Link Pod; Paveway Laser-Guided Bomb; various general purpose bombs, mines and rockets

**Date Deployed:** First flight in November 1995

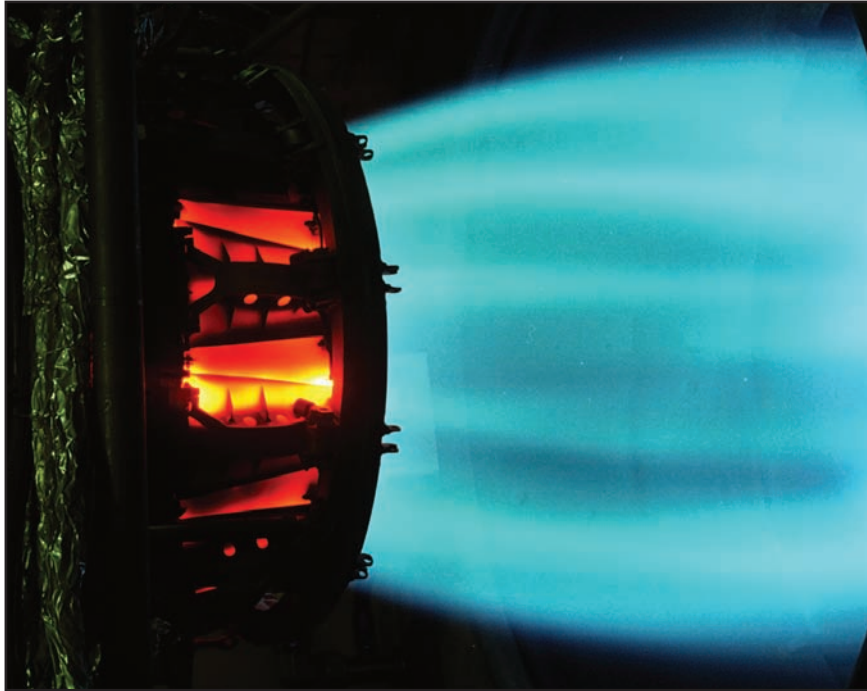
**Inventory:** 300

The Super Hornet passed its operational test and evaluation in November 1999 and entered full-rate production in 2000. The first fleet Super Hornet squadrons were stood up in 2001 and were deployed aboard aircraft carriers for the first time in 2002.

The F/A-18E/F shares a number of components with the original F/A-18 Hornet such as the canopy and ejection seat. The Super Hornet is about 25 percent larger than the original Hornet and has demonstrated a major increase in combat range, weapons payload and stealth, as well as room and power for the growth of future weapon systems.

The Super Hornet program won the first ever Department of Defense (DoD) Acquisition Excellence award for on-time, below-cost and better-than-specification performance at first flight. The program also won the Order of Daedalian and the National Aeronautic Association’s Collier Trophy for top aeronautical achievement in the U.S. AEDC was instrumental in the program’s exceptional success.

As early as 1993, AEDC was testing the General Electric (GE) F414-GE-400 engine. The Super Hornet is powered by two F414s that produce a combined 44,000 pounds of thrust. The F414-GE-400 has a 9-to-1 thrust to weight ratio, which is one of the highest ratios for a fighter engine.



With more than 2,000 hours of altitude testing logged, AEDC engineers continue to test the F414-GE-400, the power plant for the Navy's F/A-18E/F Super Hornet fighter. The engine has an increased thrust, an improved thrust-to-weight ratio of 9-to-1 and a 3-to-4-percent cruise-specific fuel consumption improvement over the F404-GE-400 engine.

More than 2,000 hours of altitude testing have been performed on the GE engines. AEDC engine tests focused on three specific milestones: Preliminary Flight Qualification (PFQ) test in May 1995; Limited Production Qualification (LPQ) tests in September 1996; and Full Production Qualification (FPQ) tests in September 1997.

The Navy's design for the Super Hornet engine inlet underwent wind tunnel testing in 1992.

Three models were tested in both the center's 16-foot transonic (16T) and supersonic (16S) wind tunnels to determine inlet performance. The inlet, which directs air to the aircraft engine, was evaluated on how effectively air travels into the inlet, through the duct and into the engine, determining fuel efficiency, mission range and flight performance.

Air flow quality at the aerodynamic interface plane was evaluated using a measurement device consisting of eight rakes with five pressure probes each. Each probe had a high-response pressure transducer to measure flow dynamics and a steady-state pressure

transducer to measure steady-state properties. Inlet and duct pressure data determined what modifications should be implemented to improved system performance.

In 1998, AEDC performed a series of 10 store separation tests in 16T. During the tests, engineers evaluated the additional tanker and strike/fighter capability of the Super Hornet using 1/10-scale aircraft and store models. The test series was designed to achieve a more cost-effective and lower risk flight test program.

Stores for the test included the JDAM and JSOW, 330- and 480-gallon fuel tanks, the AIM-7M Sparrow missile, the AGM-88 High-speed Anti-Radiation Missile (HARM) and the Mk-84 low drag bomb.

The series' primary objectives included obtaining store separation data for the developmental weapons and stores released from the five wet-station or "tanker"

configuration. From the first test in July 1993 until early 2000, data for 45 store types released from hundreds of aircraft store loadout configurations were evaluated in approximately 4,400 test occupancy hours of wind tunnel testing. These tests helped ensure that weapons are released safely and accurately during flight. The Super Hornet sports a total of 11 weapon stations on its fuselage.



AEDC personnel prepare an F/A-18E/F model aircraft in 16T for a carriage loads test.



# B-2 Spirit

*The B-2 Spirit is a stealthy, multi-role bomber capable of delivering both conventional and nuclear munitions. Its low-observable characteristics allow it to penetrate an enemy's most advanced defenses and threaten its most valued and heavily defended targets. Its capability to penetrate air defenses and threaten retaliation provides a strong, effective deterrent and combat force well into the 21st century. The aircraft's unrefueled range is approximately 6,000 nautical miles. The B-2 has a crew of two – a pilot in the left seat and mission commander in the right. The B-2 was the first aircraft to introduce the satellite-guided JDAM in combat use.*



## Highlights of Development Testing at AEDC

- Conducted aerodynamic testing on the B-2 and ran comprehensive performance checks on the General Electric (GE) F118-GE-100, the power plant for the bomber
- Conducted separation of stores, including the Joint Direct Attack Munition (JDAM) and Joint Air-to-Surface Standoff Missile (JASSM), from the aircraft

Before the first B-2 Spirit was publicly displayed on Nov. 22, 1988, it was tested at AEDC, when engineers used Computational Fluid Dynamics (CFD) to investigate wind tunnel wall interference for a B-2 model.

Rolled out of its hangar at Air Force Plant 42, Palmdale, California, the first flight of the B-2 occurred on July 17, 1989. Whiteman Air Force Base (AFB), Missouri, is the only operational base for the B-2. The first aircraft, *Spirit of Missouri*, was delivered on Dec. 17, 1993.

In 1994, a B-2 model underwent bomb separation testing in the center's 16-foot transonic wind tunnel (16T).

A year later, AEDC personnel performed test work on scale models of a B-2 stealth bomber and a Joint Defense Attack Munition (JDAM). The center played a key role in the acquisition process by providing data to help ensure that the stores safely separated not only the B-2, but also from various other aircraft when released during flight.

AEDC performed weapon separation tests again in 1999 in 16T using the Captive Trajectory System (CTS), a computer-controlled, six-degrees-of-freedom, model-positioning system that traces the trajectory of a missile, bomb or any other external store from the aircraft to simulate weapons release.

The test team used 10-percent scale models of the B-2 aircraft and Joint Air-to-Surface Standoff Missile (JASSM) weapons to investigate the separation characteristics of the JASSM from the B-2. These store separation tests at the center supported B-2 Spirit and JASSM certification flight tests that occurred in January 2001. The JASSM is used to attack both fixed and relocatable targets from extended stand-off ranges.

AEDC collected grid, freestream and trajectory data for various aircraft and store configurations. The tests ensured that the store will separate from the aircraft without striking the bay doors or contacting any surface during launch. The acquired data were used to provide a simulation database for defining the requirements for the flight test program.

## Characteristics

**Primary Function:** Multi-role heavy bomber

**Contractor:** Northrop Grumman

**Power Plant:** Four GE F118-GE-100 engines

**Thrust:** 17,300 pounds per engine

**Wing Span:** 172 feet

**Length:** 69 feet

**Height:** 17 feet

**Maximum Speed:** High subsonic

**Maximum Takeoff Weight:** 336,500 pounds

**Ceiling:** 50,000 feet

**Range:** Intercontinental, unrefueled 6,000 nautical miles

**Crew:** Two

**Armament:** Conventional or nuclear weapons

**Date Deployed:** December 1993

**Inventory:** Active force: 20

## B-2 Spirit

At the time of this test, the B-2 was involved in a multi-stage improvement program that included expanding the aircraft's weapon inventory to include the JASSM.

The JASSM is an autonomous, long-range, conventional, air-to-ground, precision standoff weapon. JASSM certification allows the B-2 Spirit to better supplement aircraft such as the B-52 and B-1.

In 2002, the F118-GE-100 completed Digital Electronic Control (DEC) testing in test cell J-2. While at AEDC, the 19,000-pound-thrust engine underwent 35 hours of simulated flight testing to ensure that the new DEC is functionally interchangeable with the existing engine fan temperature control (EFTC) and engine monitoring system processor.

The engine was first tested in the production configuration (with the engine fan temperature control and engine monitoring system processor installed) to gather baseline engine operating data. The baseline testing was then repeated with the new DEC installed, and the data were reviewed to verify proper functionality.

Specifically, testers wanted to conduct comparisons of the EFTC and DEC steady-state performance and transient operability sequences. The project accomplished 100 percent of its test objectives, and no engine anomalies were noted.

In the spring of 2006, the F118 appeared at AEDC again; this time in test cell J-1. The test was part of General Electric's (GE) Service Life Extension Program (SLEP), which is under the Air Force's Component Improvement Program (CIP) that replaces several components of the F118, F110 and F101 engines with a common core system.

The purpose of the SLEP program is to increase sustainability and support of engine fleets while preserving the overall performance on the aircraft they power.

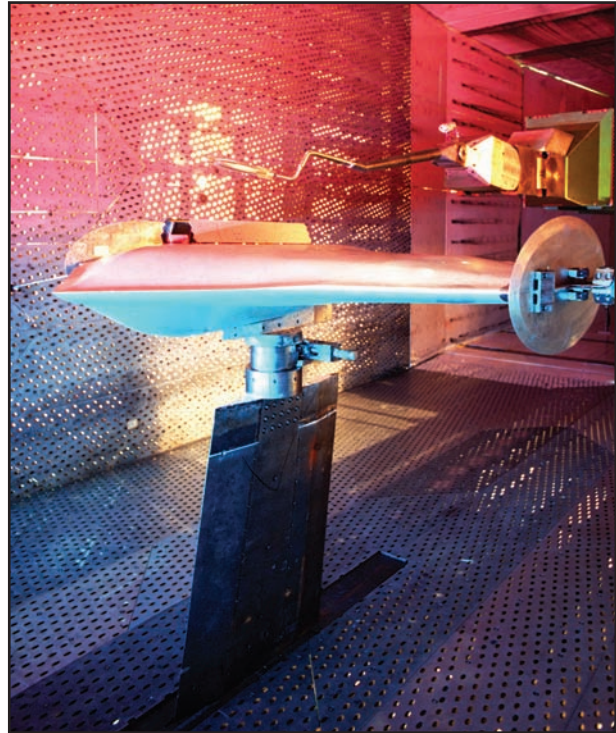
The F118-100 underwent altitude performance tests to ensure that the new engine components match the required performance for the B-2 aircraft. The tests concluded with about 90 hours of run time.

The combat effectiveness of the B-2 was proved in Operation Allied Force, where it was responsible for destroying 33 percent of all Serbian targets in the first eight weeks, by flying nonstop to Kosovo from its home base in Missouri and back.

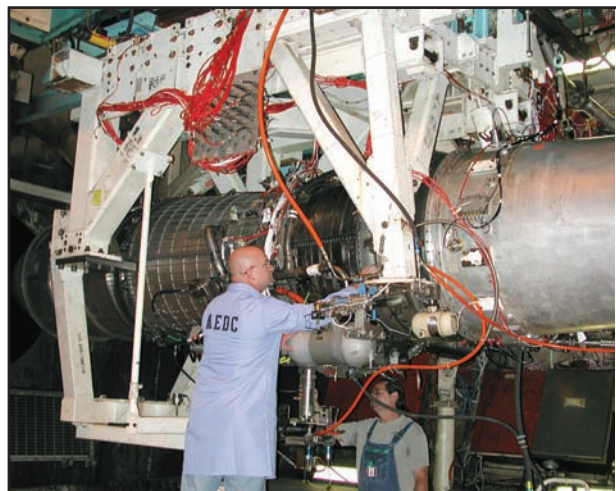
In support of Operation Enduring Freedom, the B-2 flew one of its longest missions to date, from Whiteman AFB to Afghanistan and back.

The B-2 completed its first-ever combat deployment in support of Operation Iraqi Freedom, flying 22 sorties from a forward operating location as well as 27 sorties from Whiteman AFB and releasing more than 1.5 million pounds of munitions.

The B-2's proven combat performance led to declaration of full operational capability in December 2003.



AEDC personnel performed test work on scale models of a B-2 stealth bomber and a JDAM. AEDC played a key role in the acquisition process by providing data to help ensure the bomb safely separates from various aircraft when released during flight.



Outside machinists examine components of the F118-GE-100 engine in test cell J-2 following tests to evaluate the Digital Electronic Control System. The engine completed 35 hours of testing at simulated flight conditions.

# RQ-4

## Global Hawk



*The RQ-4 Global Hawk, an unmanned aerial vehicle, has a range as far as 12,000 nautical miles, at altitudes up to 65,000 feet, flying at speeds approaching 400 mph for as long as 35 hours. The Global Hawk can fly 1,200 miles to an area of interest and remain on station for 24 hours. Cruising at extremely high altitudes, Global Hawk can survey large geographic areas with pinpoint accuracy, to give military decision-makers the most current information about enemy location, resources and personnel. After programming, the Global Hawk is capable of autonomous taxi, take off, cruise, on station loiter to capture imagery, return and landing.*

### Characteristics

**Primary Function:** Unmanned surveillance and reconnaissance  
**Contractor:** Northrop Grumman  
**Power Plant:** Rolls-Royce North American AE 3007H  
**Thrust:** 7,600 pounds  
**Wing Span:** 116 feet  
**Length:** 44 feet  
**Height:** 15 feet, 2 inches  
**Maximum Speed:** 391 miles per hour  
**Maximum Takeoff Weight:** 25,000 pounds  
**Ceiling:** 65,000 feet  
**Range:** 12,000 nautical miles  
**Crew:** Unmanned  
**Armament:** None  
**Date Deployed:** April 20, 2000  
**Inventory:** RQ-4A: 7; RQ-4B: 3

### Highlights of Development Testing at AEDC

- **Aerodynamic testing on models of the Global Hawk's airframe and performance tests on its Rolls-Royce Allison AE3007 engine**

A testimony that AEDC's work is critical to national defense was showcased in 1996 when the "Global Hawk," an unmanned aerial reconnaissance vehicle, premiered in a rollout ceremony at Teledyne Ryan Aeronautical in San Diego, California.

Tested at AEDC in late 1995 and early 1996, the Global Hawk is packed with high-resolution sensors and satellite communications equipment. Global Hawk can stay on station over areas as large as the state of Illinois for up to 42 hours at a time while delivering finely detailed imagery to military field commanders in near real time.

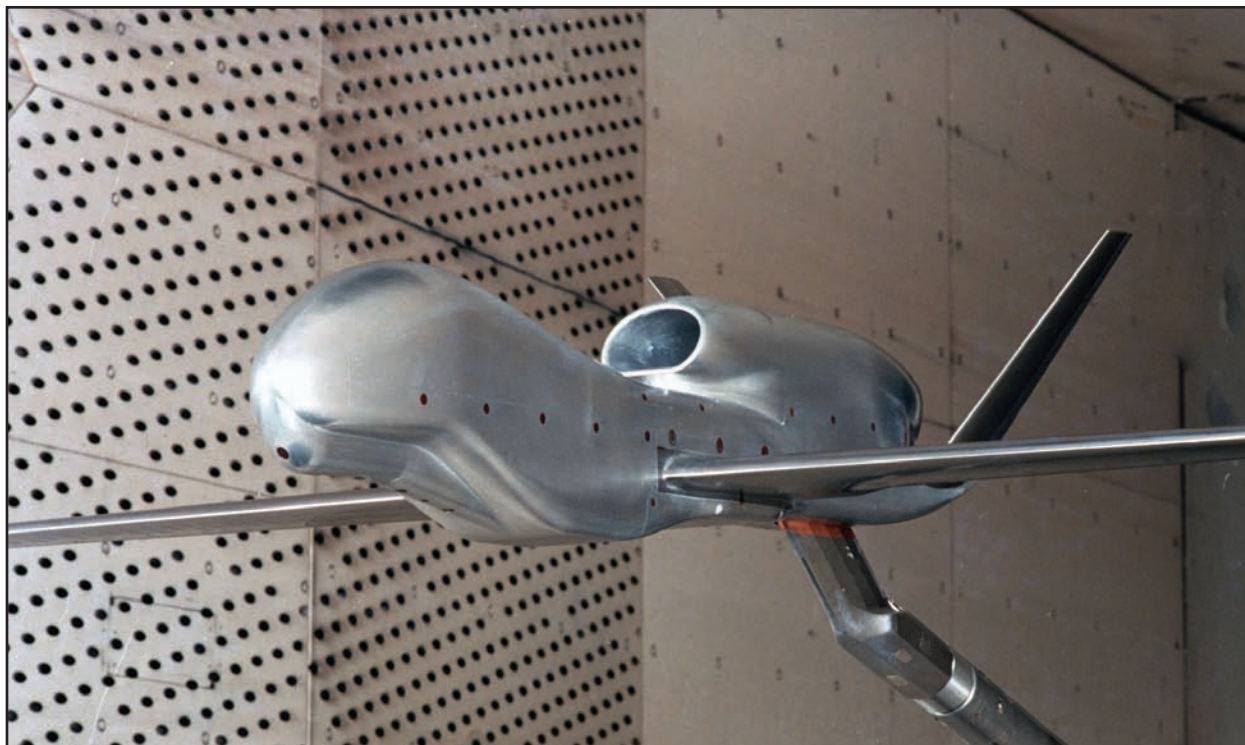
AEDC's testing of aerodynamic characteristics and control surface effectiveness provided developers with high-speed data around Mach 0.6, the approximate cruise speed for the aircraft. AEDC also provided aircraft drag information to help determine the flight range by testing the body alone and then sequentially adding the wing and tails.

One segment of the test involved the use of AEDC's Pressure Sensitive Paint (PSP) technology. The PSP technique uses a special paint and illumination source combined with an extremely sensitive camera to obtain surface pressure data. The paint glows with a brightness inversely proportional to the surface air pressure. Using PSP allowed engineers to obtain a detailed surface pressure distribution on an aircraft model that was not instrumented with conventional pressure orifices.

Power for the Global Hawk comes from a Rolls-Royce Allison AE3007 engine, which was initially tested for 69 hours in late 1995.

AEDC testing supplied the data necessary to define the design changes Allison had to incorporate in the engine to allow it to perform well at high altitudes. Prior to this AEDC test, the AE3007 engine had operated at altitudes of slightly more than 50,000 feet. The AEDC testing subjected the engine to a simulated altitude of more than 70,000 feet.

Almost three years later, the AE3007 returned to the center for additional altitude testing. The engine underwent 33 air-on hours at high altitude in AEDC's test cell T-1 to determine the engine's performance in this regime. Allison's return with the AE3007 engine allowed the engine manufacturer to evaluate engine operability at very high altitudes and to evaluate upgraded engine features as well. As a side benefit, Allison was able to compare engine performance between the two AEDC test entrants.



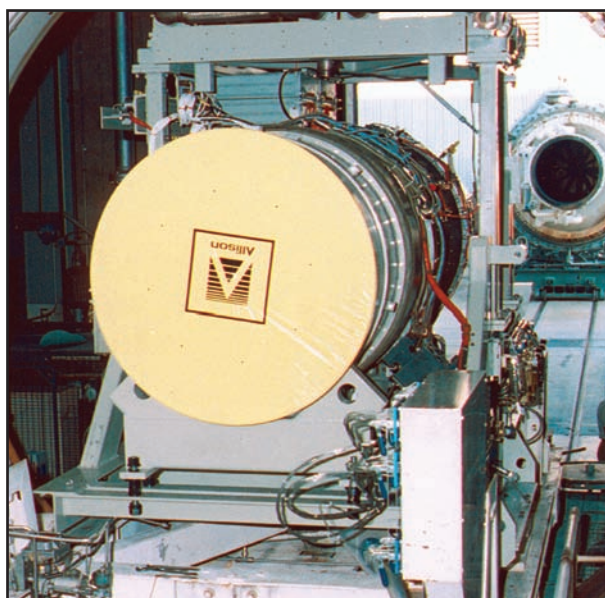
**The Global Hawk underwent testing in wind tunnel 16T, which provided aerodynamic characteristics, control surface effectiveness and drag information.**

In September 2000, a Global Hawk test occurred in the center's 16-foot transonic wind tunnel (16T) in which one of the test requirements was to obtain data in a wings-level condition while varying the side to side motion of the model relative to the wind. This required the use of a secondary roll mechanism in addition to the standard pitch and roll mechanisms normally used.

A 1996 test of the Global Hawk used this arrangement in the move-pause data acquisition mode. In an effort to acquire data in a 'faster, better, cheaper' environment, AEDC engineers were determined to apply the continuous-sweep data acquisition technique to the wings-level-yaw test article movement. Continuous sweep had been successfully used in 16T for a 2-degree-of-freedom (pitch and roll) system. However, adding a third degree of movement and coordinating the movement of three individual systems would be a significant task. Nevertheless, the task was successfully completed, and the new data acquisition capability proved to be seven and a half times faster than the move-pause acquisition method while acquiring 3.6 times more data.

In 2004, the AE3007 was back at the center for high-altitude performance and operability testing in test cell T-4 to evaluate the engine's overall performance under steady-state and transient conditions and to perform surge-line mapping for the fan and compressor.

The customer wanted to determine how much power could be extracted from the engine while maintaining stable



**The Allison AE3007H, the power plant for the Global Hawk, underwent 33 air-on hours of high altitude testing, which helped the customer meet scheduled milestones.**

operation. Increased power extraction is desired to supply additional electrical power to the airframe.

During this program, test operators conducted 14 test periods encompassing 170 engine-operating hours with the engine running at simulated altitude conditions up to

67,000 feet and at simulated flight speeds up to Mach 1 to evaluate engine performance under those conditions.

To help meet the customer's critical schedule, test engineers installed a new 42-inch diffuser insert. The insert increased the amount of diffuser pumping allowing the test cell to achieve a simulated altitude up to 67,000 feet. This allowed test operators to use existing basic plant compressor and exhausters instead of the more costly Plenum Evacuation System (PES) and avoided potential PES schedule conflicts.

Test planners originally designed the program to provide 150 air-on hours of testing to meet primary test objectives. However, by using the new diffuser the team avoided the costs associated with using the PES, allowing the customer to include an additional 20 test hours to meet secondary test objectives in the program.

In addition, AEDC provided pressure bricks that were mounted on the engine to acquire engine pressures at 100 samples per second. Since Rolls-Royce used the same pressure bricks, the modules enhanced the AEDC and Rolls-Royce test facility data correlation and reduced the data measurement uncertainty.

A new Global Hawk UAV configuration, which would provide advanced capabilities for the warfighter in the War on Terror in Iraq and Afghanistan, came to AEDC in late 2006.

A model of the Global Hawk with the new configuration was tested in 16T to gather aerodynamic data to support air vehicle performance analysis and flight control system studies. The results will also be used to validate and expand the high-speed Block 20 Global Hawk database.

The configuration change is a modification to the vehicle's airframe to accommodate an advanced radar system that would enable U.S. and coalition forces to better detect, identify and track both moving and stationary ground vehicles and low-flying aircraft and cruise missiles.

The customer collected new information on an upcoming configuration – the Multi-Platform Radar Technology Insertion Program (MPRTIP) – and did some ventral fin testing.

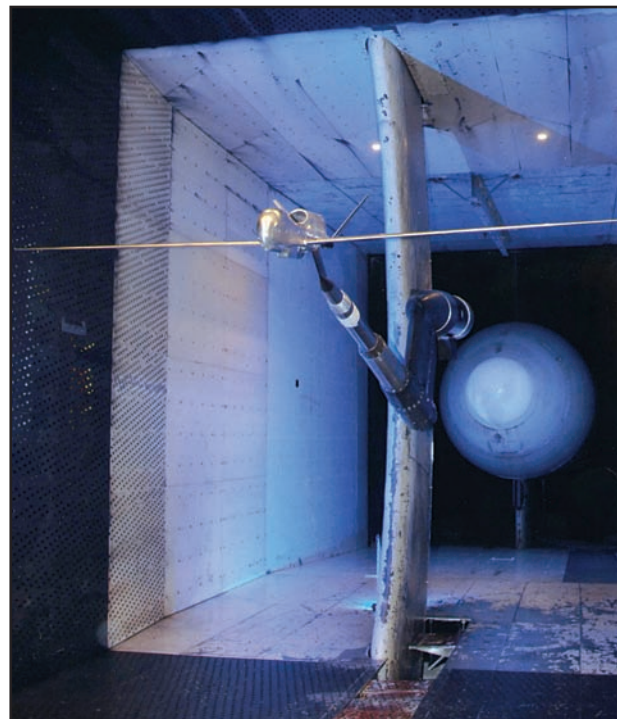
The scale model had experienced wing flexure problems during a previous low-speed wind tunnel test at the San Diego Air & Space Technology Center's Low-Speed Wind Tunnel in California and also during the Global Hawk test at AEDC in 2003. Since then, the customer had worked



**An ATA outside machinist inspects the Global Hawk model being used for aerodynamic testing in tunnel 16T in 2006.**

to fix the model's problems, and the wings now act as one single wing as opposed to two separate pieces.

The results from the testing in 16T were compared to the data obtained from the earlier test in California and to data collected from a Computational Fluid Dynamic (CFD) model.



**A model of the Global Hawk Unmanned Vehicle Block 20 was tested in tunnel 16T in 2006.**

# F-35

## Joint Strike Fighter Lightning II

*The F-35 Lightning II Joint Strike Fighter is a fifth-generation, multi-role fighter designed for use by the U.S. Air Force, Navy and Marine Corps, the Royal Navy and Air Force and other allied defense forces. Three F-35 variants have been tested, thus maximizing commonalities and reducing production and maintenance costs. The U. S. Air Force will utilize the Conventional Take Off and Landing variant, the U.S. Navy will use the Carrier Variant and the Marines will use the Short Take Off/Vertical Landing variant.*



### Highlights of Development Testing at AEDC

- More than 10,000 hours of wind tunnel testing on models of the F-35 and engine testing on the Pratt & Whitney (P&W) F135-PW-100 and the Fighter Engine Team (FET) F136 engines
- Evaluation of the separation characteristics of the AIM-120, Joint Direct Attack Munition (JDAM), Paveway II and C-13 external fuel tanks from the F-35 in wind tunnel 4T

AEDC teamed with Lockheed Martin in an integrated test and evaluation effort to support design and development of the F-35 Lightning II Joint Strike Fighter (JSF).

The initial flight of the new JSF in December 2006 came after more than eight years of development of the JSF and testing at AEDC.

Center engineers have tested the new weapon system under various scenarios and flight conditions. The F135 and F136 engines and wind tunnel models of the aircraft have logged more than 10,000 hours in AEDC facilities, ensuring that the F-35 was ready for its initial flight.

Formerly known as the Joint Advanced Strike Technology (JAST) Program, the JSF program is the Department of Defense's (DoD) focal point for defining affordable next-generation strike aircraft weapon systems for the Navy, Air Force, Marines and U.S. allies.

The focus of the program is affordability – reducing the development, production and ownership costs of the JSF family of aircraft. The program made headway toward this goal by facilitating the services' development of fully validated, affordable operational requirements and lowering risk by investing in and demonstrating key leveraging technologies and operational concepts prior to the start of engineering and manufacturing development (EMD) of the JSF in 2001.

In fiscal year 1997, the JSF Program Office awarded P&W the Propulsion Ground and Flight Demonstration Program contract to provide flight-qualified engines for the JSF Weapon System Contractor (WSC) Concept Demonstration Aircraft (CDA). AEDC's testing supported the Services' selection of an engine-airframe combination for the Preferred Weapons System Concept (PWSC).

AEDC began testing the competing JSF engine configurations in the

### Characteristics

#### F-35A Conventional Take Off and Landing (CTOL)

**Primary Function:** Tactical Fighter  
**Contractor:** Lockheed-Martin  
**Power Plant:** One P&W F135 or GE/RR F136 afterburning turbofan  
**Thrust:** 40,000 pounds  
**Wing Span:** 35 feet  
**Length:** 51.5 feet  
**Height:** 14 feet, 2 inches  
**Maximum Speed:** Mach 1.6  
**Maximum Takeoff Weight:** In excess of 50,000 pounds  
**Ceiling:** 48,000 feet  
**Range:** more than 1,200 nautical miles on internal fuel  
**Crew:** One  
**Armament:** A wide selection of U.S. and UK air-to-air and air-to-ground weapons including AMRAAM, ASRAAM, JDAM, laser-guided bombs and an internally mounted 25-millimeter gun  
**Date Deployed:** Scheduled for service in 2011  
**Inventory:** N/A

## Characteristics

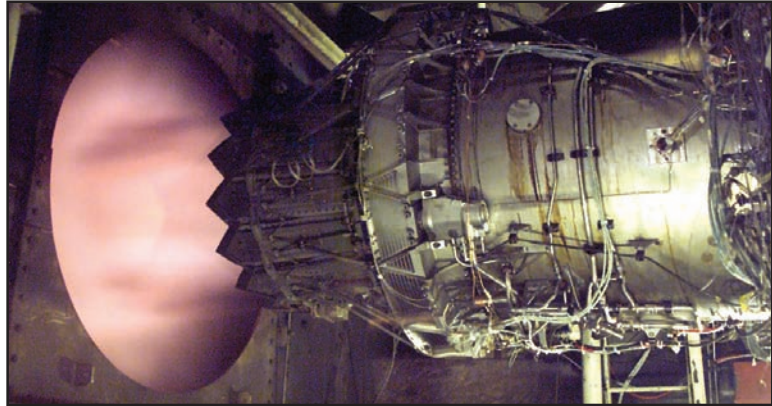
### F-35B Short Take Off/Vertical Landing (STOVL)

**Primary Function:** multi-role stealth fighter  
**Contractor:** Lockheed Martin  
**Powerplant:** P&W F135 or GE F136  
**Thrust:** 40,000 lb (with afterburner)  
**Wingspan:** 35 ft  
**Length:** 51.3  
**Height:** 14.2  
**Weight:** 32,000 empty  
**Maximum Takeoff Weight:** 60,000  
**Range:** 900 nmi  
**Ceiling:** 60,000 ft  
**Armament:** standard weapons load is two AIM-120C air-to-air missiles and two 1,000-pound GBU-32 JDAM guided bombs. Optional internal loads include six GBU-38 small-diameter bombs, as well as a wide variety of air-to-ground missiles, dispensers and guided weapons  
**Crew:** one  
**Inventory:** n/a

## Characteristics

### F-35C Carrier Variant (CV)

**Primary function:** multi-role stealth fighter  
**Contractor:** Lockheed Martin  
**Powerplant:** P&W F135 or GE F136  
**Thrust:** 40,000 lb (with afterburner)  
**Wingspan:** 43 ft  
**Length:** 51.5 ft  
**Height:** 14.9 ft  
**Weight:** 34,800 lb (empty)  
**Maximum Takeoff Weight:** 70,000 lb class  
**Fuel Capacity:** 19,000+ lbs  
**Maximum Speed:** approximately 1,200 mph (Mach 1.6)  
**Range:** 1,400 nmi  
**Ceiling:** 60,000 ft  
**Armament:** 1 GAU-22/A mm cannon, fitted as an external pod with 220 rounds, 6 external pylons on wings and 2 internal bays with 2 pylons each. Internal missiles, 4 air-to-air missiles, or 2 air-to-air missiles and 2 air-to-ground weapons. External missiles, 6 air-to-air missiles or 4 air-to-ground weapons and 2 air-to-air missiles. Also, SDB's and JDAM series.  
**Crew:** one  
**Inventory:** n/a



The P&W F135 engine undergoes altitude testing in AEDC's J-2 test cell. The J-2 test cell has the capability to simulate altitudes up to 80,000 feet and speeds up to Mach 3.

fall of 1998. The tests, which were conducted in propulsion development test cell C-2, tested both the Boeing and Lockheed versions of the F119 JSF engines. The Lockheed version was tested first, then the cell was converted to test the Boeing version of the engine.

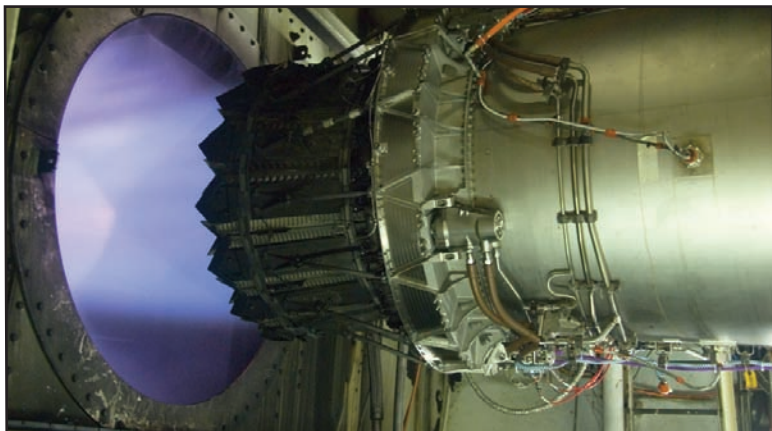
The primary propulsion systems being designed for the JSF program were derivatives of the F119-PW-100 engine, which powers the F-22A Raptor. The propulsion system concepts for the Boeing and Lockheed Martin configurations utilize new fan and low-pressure turbine (LPT) designs, which are based on F119 designs, materials and processes.

By 1999, P&W's JSF F119 derivative engines had undergone more than 1,400 hours of testing in propulsion development test cell J-2.

AEDC has spent about \$17 million on facilities upgrades; most of these were specifically and uniquely required for the JSF engine. The F135 marks an evolution in the art of designing aircraft engines – more airflow, more thrust – things that legacy aircraft engine programs have not required.

Engine test program costs at AEDC, ranging from facility upgrades that began in 2001 through Operational Capability Release (OCR), are nearly \$200 million.

In 2003, a team at AEDC tested an F135 P&W engine combustor in propulsion development test cell T-11, kicking off an eight-month test program. (The F135 combustor test was also conducted in test cell T-4 in 1996 which was the first propulsion-related testing for the CDA JSF.)



A General Electric/Rolls-Royce F136 engine, the alternate power plant for the F-35 Lightning II JSF, being tested at intermediate power conditions.

## F-35 Joint Strike Fighter Lightning II

The test data enabled P&W to determine the best combustor hardware configuration for the first Systems Development & Demonstration (SDD) engine, which was tested at the company's West Palm Beach, Florida, facility later that year.

On April 15, 2004, the first F135 JSF engine slated for qualification testing arrived for entry into propulsion development test cell J-2. In the late summer of 2006, AEDC engineers completed qualification testing on the Conventional Take Off and Landing (CTOL) variant of the next generation multi-role strike fighter, which flew its initial flight in late 2006 as the F-35A.

The Short Take Off and Vertical Landing (STOVL) version, the F-35B, will be used by the Marines and the British Royal Navy. Finally, the F-35C is the carrier version (CV), which will be used by the U.S. Navy.

All three versions have been tested in AEDC's wind tunnels. There is not a lot of difference aerodynamically between the CTOL and STOVL versions; however, the CV has much larger wings for creating the greater lift necessary to land on a carrier deck.

In September 2006, AEDC completed aerodynamic testing on two variants of the F-35 in support of flight testing. With this test, the AEDC staff surpassed 8,000 hours of JSF testing in the center's Propulsion Wind Tunnel (PWT) facility in support of the system design and development phase of the program.

Although the aircraft has reached initial flight capability, the work continues for AEDC engineers. For example, they are already preparing for salt spray corrosion testing for the Navy engines to look at suitability and survivability of the engine in an aircraft carrier environment.

A new AEDC F-35 testing chapter began in 2007 when an alternative power plant for the F-35, the GE/Rolls-Royce F136 engine arrived at the center.

Complementing the center's engine and aerodynamic testing described above, the analysis and Computation Fluid Dynamics (CFD) calculations provided at the center have been instrumental in support of JSF aircraft development. Time-critical computations have been used to support and augment wind tunnel testing for aircraft/weapons loading and store separation.

Using high-performance computing resources and AEDC personnel, the center has also provided CFD calculations to

aid test planning and to supplement and interpret test data.

These calculations have primarily supported internal and external weapons separation characteristics and structural analysis for aircraft weapons loadings. These computations have also helped with the analysis of the optical window loads for the targeting system, the canopy and of the weapons bay. Additional computations helped to determine the separation behavior of the canopy.

CFD was used to provide the flow field around the vehicle and inside the weapons bays. The standard "re-usable" trajectory generation codes, developed to support other weapon systems, were used for separation performance analysis for the weapons released from the vehicle. AEDC also provided parametric analyses of flight conditions, weapons' physical characteristics variations and launch conditions.

More than 500 CFD flow-field computations have been performed in support of JSF development at AEDC. These computations were performed for all variants to simulate a variety of store loadings and flight conditions.



A 12-percent model of the STOVL version of the F-35 Lightning II undergoes aerodynamic load testing in the center's 16T wind tunnel.



A Lockheed Martin engineer inspects the JSF model during a break in aerodynamics load testing in wind tunnel 16T.



An ATA craftsman examines the STOVL F-35 model in wind tunnel 16T during a model change. The information from this testing, the final entry in a series of tests, went into a large database to refine and validate the aircraft designs for flight testing.



# EA-18 Growler

*The EA-18 Growler is being developed to replace the Navy's current carrier-based EA-6B Prowler. The next-generation Navy electronic attack aircraft combines the combat-proven F/A-18 Super Hornet with a state-of-the-art electronic warfare avionics suite. The EA-18G features an airborne electronic attack suite based on Northrop Grumman's Improved Capability III system, a radically new jamming and information warfare system. The first EA-18G rolled out on Aug. 3, 2006, and the first flight followed on Aug. 15, 2006, with Initial Operating Capability for the EA-18 in 2009.*

## Characteristics

**Primary Function:** Carrier-based escort electronic warfare  
**Contractor:** Boeing  
**Power Plant:** Two F414-GE-400  
**Thrust:** 44,000 pounds per engine  
**Wing Span:** 44 feet, 8.5 inches  
**Length:** 60 feet, 1.25 inches  
**Height:** 16 feet  
**Maximum Speed:** In excess of Mach 1.8 at high altitude  
**Maximum Takeoff Weight:** 66,000 pounds  
**Ceiling:** >50,000 feet  
**Range:** 681 miles on hi-hi-hi interdiction mission  
**Crew:** Two  
**Armament:** Exact loadouts for EA-18G TBD; 11 external weapons stations with capacity up to 17,750 pounds; two wingtip LAU-127 launchers for Sidewinder; six removable under-wing-mounted hard points (four inner with increased carriage capability), two multi-mode conformal fuselage stations, one centerline fuselage removable hardpoint usually used for fuel or refueling store  
**Date Deployed:** Not yet in service  
**Inventory:** 2



## Highlights of Development Testing at AEDC

- **64.5 hours of store separation testing to support development of the EA-18**

In addition to extensive testing on its predecessor, the Super Hornet, AEDC has also been involved in developmental testing of the EA-18G Growler.

The EA-18G, an electronic attack version of the F/A-18E/F aircraft, is the planned replacement for the Navy EA-6B Prowler, in service since 1971.

AEDC has a 10-percent scale model of an F/A-18E/F that has been tested many times in 16T in the last 10 years, and engineers were able to draw on some experience from that testing.

AEDC conducted 65 air-on hours of store separation testing in late 2005 to support development of the EA-18G.

Store separation testing for the F/A-18 E/F also provided benchmark data on the aerodynamic performance of the EA-18G.

Since store separation data on the AN/ALQ-99 tactical jamming pod had never been defined before, there were no freestream data on how it would react to airflow. The tests, which laid the groundwork for future related testing, served to define the aerodynamic behavior of the pods on the wings of the aircraft as well as the flight envelope within which it can be safely jettisoned from the plane.

The purpose of the test program was to obtain the separation characteristics of the jamming pods, an external fuel tank, an AGM-88 High-Speed Anti-Radiation Missile (HARM) air-to-ground missile (launch mode), an AGM-88/LAU-118 (jettison mode) and an AIM-120C air-to-air missile in the launch mode.

Testing was conducted within a range from Mach 0.6 to 1.20 in support of flight testing and storage carriage and release certification.



**An outside machinist speaks through a microphone to test personnel in the 16T control room who are operating the metal arm, or sting, with a wing store above the EA-18G model.**

# P-8A Poseidon

*The Navy's replacement platform for the P-3C Orion, the P-8A Poseidon, will transform how the Navy's maritime patrol and reconnaissance force mans, trains, operates and deploys. The P-8A will provide more combat capability from a smaller force and reduced infrastructure while focusing on worldwide responsiveness and interoperability with traditional manned forces and evolving unmanned sensors. The P-8A Poseidon, a modified Boeing 737-800ERX, brings together a highly reliable airframe and high-bypass turbofan jet engine with a fully connected, state-of-the-art open architecture mission system.*

## Characteristics

**Primary Function:** Anti-Submarine and Anti-Surface Warfare  
**Contractor:** Boeing IDS  
**Power Plant:** Two CFM56 turbofan engines  
**Thrust:** 27,000 pounds per engine  
**Wingspan:** 117 feet, 2 inches  
**Length:** 129 feet, 5 inches  
**Height:** 42 feet, 1 inch  
**Maximum Speed:** 563 miles per hour  
**Maximum Takeoff Weight:** 182,000 pounds  
**Ceiling:** 41,000 feet  
**Range:** 1,200 nautical miles with four hours on station  
**Crew:** Flight: Two; Mission: Seven  
**Armament:** Torpedoes, cruise missiles, bombs, mines  
**Date Deployed:** First squadron is planned for 2013  
**Inventory:** 0



## Highlights of Development Testing at AEDC

- **Store separation testing of torpedoes, missiles and Naval mines**

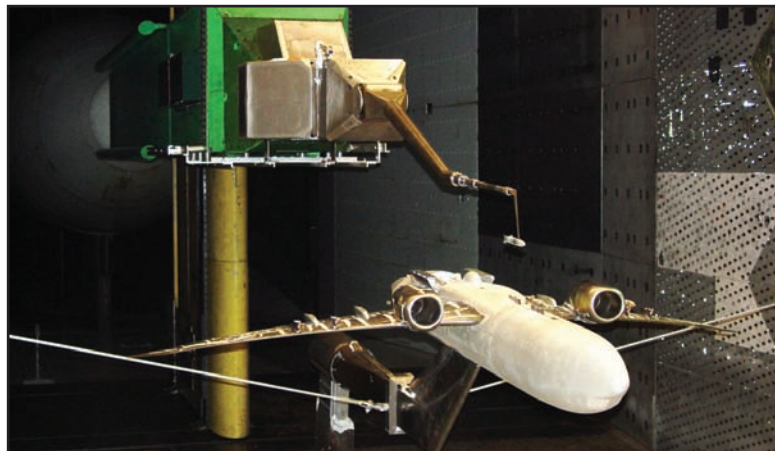
In early 2006, AEDC successfully completed P-8A Poseidon weapons separation tests in 16T.

The tests validated Boeing's predictions that the Navy-required P-8A weapons, which include torpedoes, missiles and naval mines, will safely separate from the aircraft when launched during flight.

While the Navy had planned two test entries at AEDC, all data needed were obtained in the first entry.

Boeing was awarded the contract to develop the P-8A on June 14, 2004. The P-8A is a derivative of a modified Boeing 737-800ERX airliner and brings together a reliable airframe and high-bypass turbofan jet engine with a fully connected, state-of-the-art open architecture mission system. Coupled with next-generation sensors, the P-8A will dramatically improve anti-submarine and anti-surface warfare capabilities. The P-8A program went through a preliminary design review in November 2005.

The Navy plans to purchase 108 production P-8As. The first aircraft is scheduled to be delivered for flight test in 2009, with initial operating capability (IOC) planned for 2013.



The P-8A Poseidon weapons separation tests were successfully completed in 16T. The tests validated Boeing predictions that the U.S. Navy-required P-8A weapons will safely separate from the aircraft when launched during flight.



# Space Systems



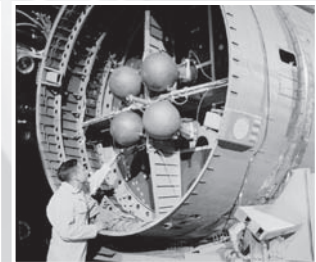
Global Positioning Satellite



Apollo



Crew Exploration Vehicle



Gemini

# Space Systems Overview

As the nation moves deeper into the 21st century, AEDC remains firmly dedicated to support testing of space systems, rocket motors and missile systems.

Long before man made it to the moon or the Patriot missile became known as the “Scud buster,” these systems occupied the wind tunnels, arc heaters and ranges of AEDC.

AEDC has an unprecedented capability for testing and evaluating rocket engines under simulated altitude conditions, testing more than 3,000 engines from small STAR motors to large liquid engines like those used on the Saturn IIB. Additionally, missile systems like Air-Launched Cruise Missiles (ALCM) and Submarine-Launched Ballistic Missiles (SLBM) saw numerous hours in both the wind tunnel and engine test facilities. Other systems like the Pershing, Sergeant Missile, Snark and Nike have also spent time in the center’s test cells.

To meet the growing test requirements resulting from increased use of liquid-propellant space boosters, the center returned to testing large liquid storable and cryogenic-propellant rocket engines after a hiatus of nearly 20 years.

The center played a key role in keeping the Titan IV, America’s only expendable, heavy-lift launch vehicle, from being grounded by qualification testing of a new Stage II engine and has tested the next generation RL-10 engine.

In the spring of 2007, the center conducted its 27<sup>th</sup> test on the Peacekeeper Stage III rocket engine to determine the effect of age on the performance of the solid rocket motor. In March 2009, an upper-stage Minuteman became the 100<sup>th</sup> rocket motor to be successfully fired in the J-6 Large Rocket Motor Test Facility.

Part of America’s nuclear deterrent force from 1986 to 2005, the Peacekeeper Intercontinental Ballistic Missile (ICBM), the center supported the development, flight proof, qualification, production quality assurance and aging and surveillance programs.

True to AEDC’s vision of being the center of knowledge for simulated rocket testing, center employees have completed a number of initiatives to improve the scope and quality of the products available to users. These include: statistical analyses

of aging trends in solid rocket motors, hosting the Minuteman Propulsion System Rocket Engine database, advancements in liquid rocket engine health monitoring, and improved test information handling, storage and retrieval.

Since the late 1950s, AEDC supported the nation’s space exploration programs beginning with Discoverer, Pioneer, Mariner and Surveyor and continuing with manned spaceflight programs, including Mercury, Gemini, Apollo and the space shuttle.

AEDC has supported the development and integration of technologies into operational space systems by simulating the expected operational environment and assessing design performance using a variety of test cells – wind tunnels, thermal vacuum chambers and rocket altitude test cells.

The journey to space began for AEDC March 27, 1957, when the aerodynamic loads a rocket would experience at escape velocity (25,000 mph) were measured in AEDC’s von Kármán Gas Dynamics Facility. The following year, engineers in the Engine Test Facility test fired their first solid-propellant rocket motor for the third-stage of a space vehicle. In 1959, the first wind tunnel tests were performed on a model that would evolve into the Saturn V rocket.

During the 1960s, AEDC conducted some 55,000 hours of test support for the Apollo program, involving 25 of the center’s then 40 test facilities. These tests included simulated reentry tests where thermal protection materials were evaluated. From 1960 to 1968, AEDC conducted more than 3,300 hours of wind tunnel tests, representing more than 35 percent of all of NASA’s Apollo wind tunnel tests. From June 1965 to June 1970, 340 rocket engines were fired in the single largest test program ever conducted at the center to man-rate the Saturn V upper stages.

During the 1970s, NASA’s emphasis shifted from deep space exploration to near Earth space operations and development of Skylab and the Space Transportation System known as the space shuttle. During that time, AEDC evaluated various model configurations for the space shuttle program, obtaining data on heat transfer, aerodynamic forces and pressures. These tests helped determine the appropriate construction materials and establish baseline flight models for the

ascent portion of the mission. The tests also included separation predictions for the two strap-on solid propellant boosters from the shuttle after burnout.

AEDC has supported NASA throughout space shuttle operations, as required, to address potential operational scenarios and anomalies. In the 1980s, wind tunnel tests assessed the effect of a space shuttle main engine failure during the initial stages of ascent. In the 1990s, space shuttle insulation materials used to protect the shuttle's external fuel tanks were reassessed.

AEDC also supported several aspects of the space shuttle "return-to-flight" program following the Columbia accident. The objective of the tests was to flight-qualify the redesign of the bipod fixture that connects the liquid fuel tank to the shuttle.

AEDC also supported development of technologies on several NASA space probes and experiments. The protective nosetip material for the Galileo Space Probe that sampled Jupiter's atmosphere in 1995 was evaluated by launching scale models at 11,000 mph down the AEDC 1,000-foot-long hyper-ballistic Range G.

The NASA/European Space Agency Cassini mission to Saturn deployed a probe to Saturn's moon, Titan, to assess the moon's environment. The Huygens probe deployed a parachute for its descent. Drag data was acquired in 16T on a model of the Huygens probe.

In another NASA/ESA joint venture, an Infrared Sub-millimeter Telescope mirror was calibrated in the AEDC 10V sensor calibration chamber to support sky-mapping efforts.

Deployment of structures in space after launch presents another considerable design challenge. AEDC tested solar panels for NASA's Microwave Anisotropy Probe (MAP) to determine if the panels would deploy properly in space and routinely discusses potential investigations supporting development of NASA missions.

AEDC has supported NASA at both its two remote operating locations – the Hypervelocity Wind Tunnel 9 Facility in Silver Spring, Md., and the National Full-Scale Aerodynamic Facility (NFAC) at Moffett Field, Calif., making numerous contributions to NASA. Most recently, both facilities have supported the development of the Mars Science Laboratory (MSL).

AEDC has laid the foundation for a new capability – the Space Threat Assessment Testbed (STAT) ground test capability – with the awarding of a contract in October 2008.

STAT will create a realistic space environment to perform developmental and early operational testing of space hardware for the Department of Defense, the National Reconnaissance Office and other agencies against man-made threats and naturally occurring environmental phenomena. STAT will simulate the environmental conditions existing at various orbits and self-induced effects and will emulate man-made threats to perform system test and evaluation. It will also lay the foundation for near real-time connectivity to a satellite operations center. It will allow the center to do integrated system testing, training, tactics, techniques and procedures development and represents a significant step toward the development of an important new national capability.

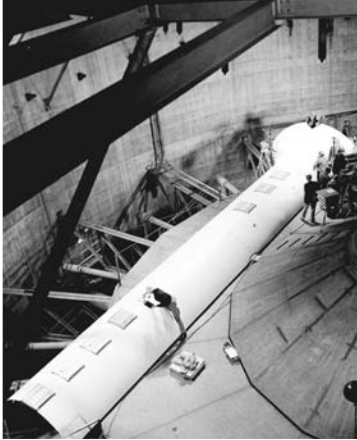


# Space Systems Timeline

## The 1950s

### Project Mercury

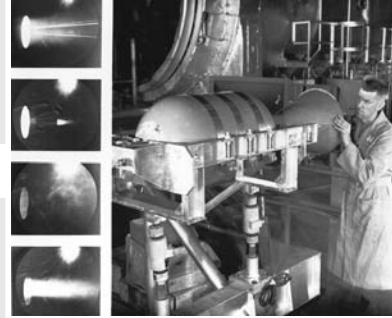
Discoverer



Voyager

### Project Gemini

Vanguard



Vanguard

## The 1960s

Voyager

Project Apollo

Scout

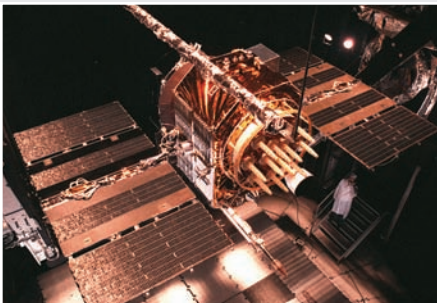
Viking

Voyager

## The 1970s

### Space Transportation System

GPS



Global Positioning System (GPS)



Space Transportation System

## The 1980s

## The 1990s

### International Space Station

EELV

X-33

### Cassini-Hugens

Chandra

Pathfinder



GOES-M



Pathfinder

## The 2000s

GOES-M

X-37

X-43 Hyper-X

Crew Exploration Vehicle  
Mars Science Laboratory

# Project Mercury

Initiated in 1958, completed in 1963, Project Mercury was the United States' first man-in-space program. The objectives of the program, which made six manned flights from 1961 to 1963, were specific: to orbit a manned spacecraft around Earth; to investigate man's ability to function in space; and to recover both man and spacecraft safely. Mercury was a cone-shaped, one-man capsule with a cylinder mounted on top and an escape tower fastened to the cylinder of the capsule. The Mercury program used two launch vehicles – a Redstone for the suborbital flight and an Atlas for the four orbital flights. Prior to the six manned flights, unmanned tests were made of the booster and the capsule, carrying a chimpanzee.



## Highlights of Development Testing at AEDC

- Escape tower rockets
- Retrorockets
- Reentry



A 1960 Mercury escape tower test in 16T improved stability to prevent tumbling in the event of an emergency abort during satellite launch.

## Characteristics (Mercury Capsule)

**Primary function:** Suborbital and orbital spaceflight  
**Contractor:** McDonnell  
**Power Plant:** Redstone rocket (suborbital), Atlas (orbital)  
**Diameter:** 6.2 feet  
**Height:** 11.5 feet  
**Maximum Takeoff Weight:** 2,000 pounds  
**Crew:** One  
**First Launched:** 1963

During the Project Mercury era, AEDC provided critical testing on components of the spacecraft.

AEDC conducted tests in September 1959 in support of Project Mercury. In one, a 1/3-scale model of the space capsule, designed to carry man into orbit around the Earth, was tested in the 16-foot transonic wind tunnel (16T) to determine static stability for two capsule configurations.

In 1963, Maj. Gen. William L. Rogers, then AEDC commander, stressed the importance of AEDC tests in support of Project Mercury at a presentation he gave in Pittsburgh.

*“This is a scaled-down model of the Mercury capsule with escape tower attached. It’s mounted in the 16-foot test section of our largest transonic wind tunnel. Purpose of these tests was to find out if the capsule with the tower attached would be stable – that is, would not oscillate – if the astronaut had to get away from the booster rocket in a hurry before booster*

## Project Mercury



The Project Mercury model was tested in the center's 16T wind tunnel.

burnout. As it turned out, these tests showed that original configuration was not as stable as it should have been. However, modifications made as the result of the first tests proved in later tests to be the answer to the problem.

“And this is the 60,000-pound-thrust escape rocket that’s mounted at the top of the escape tower. This is the full-scale motor in one of our rocket test cells. The reason for this test was to make sure that the ignition unit would operate properly at a given altitude.

“The test showed that the unit worked all right. Fortunately, none of the astronauts ever had to put the escape system to an actual flight test.

“I might mention that we also tested the retrorockets – the motors that slow the capsule down to begin reentry – under similar conditions. They worked in the test cell, and they did in actual flight.

“This is a smaller scale model of the capsule being tested in a tunnel we call the 50-inch hypervelocity tunnel. In these tests, we simulated conditions encountered by the capsule during the initial stages of reentry to make sure that it could withstand the extreme temperatures and pressures involved.”



The original seven Mercury astronauts were, from left, front row: Virgil “Gus” Grissom, Scott Carpenter, Donald “Deke” Slayton and Gordon Cooper, back row: Alan Shepard, Walter Schirra and John Glenn. (NASA photo)



# Project Gemini

Three weeks after Alan Shepard became the first American in space, President John F. Kennedy announced the goal of sending astronauts to the moon before the end of the decade. NASA expanded the existing manned space flight program to include the development of a two-man spacecraft – officially designated Gemini on Jan. 3, 1962. The Gemini Program had four objectives – to subject astronauts to long-duration flights, a requirement for projected later trips to the moon or deeper space; to develop effective methods of rendezvous and docking with other orbiting vehicles and of maneuvering the docked vehicles in space; to perfect methods of reentry and landing the spacecraft at a preselected landing point; and to gain additional information concerning the effects of weightlessness on the crew and record their physiological reactions during long-duration flights.

## Characteristics (Gemini Capsule)

**Primary Function:** Orbital spaceflight  
**Contractor:** McDonnell  
**Power Plant:** Titan II Rocket  
**Length:** 19 feet  
**Diameter:** 10 feet  
**Height:** 8 feet, 6 inches tall  
**Maximum Takeoff Weight:** Approximately 4,500 pounds  
**Crew:** Two  
**First Crewed Launch:** March 23, 1965  
**Crew:** 2

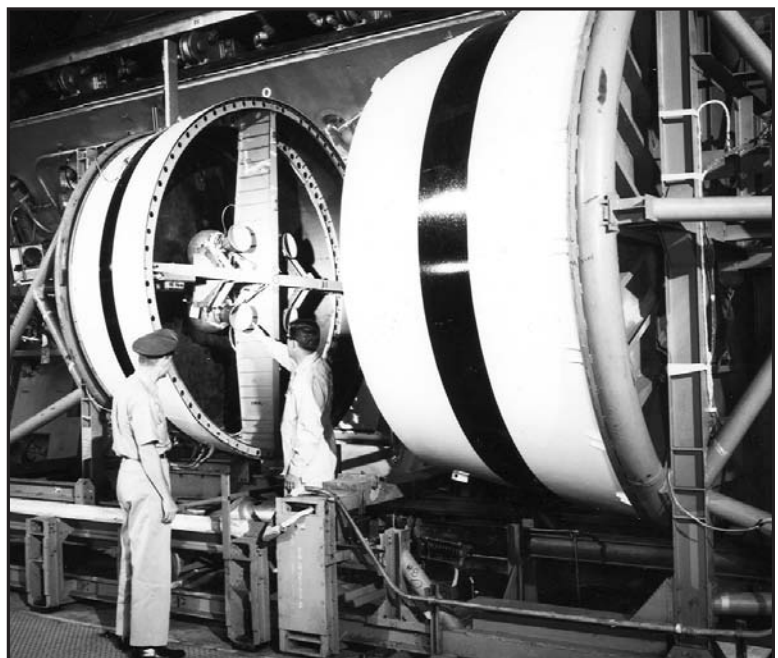


## Highlights of AEDC Contributions

- **Agena engine tests at altitude**
- **Escape tower emergency abort**
- **Reentry aerodynamics and aerothermal testing**

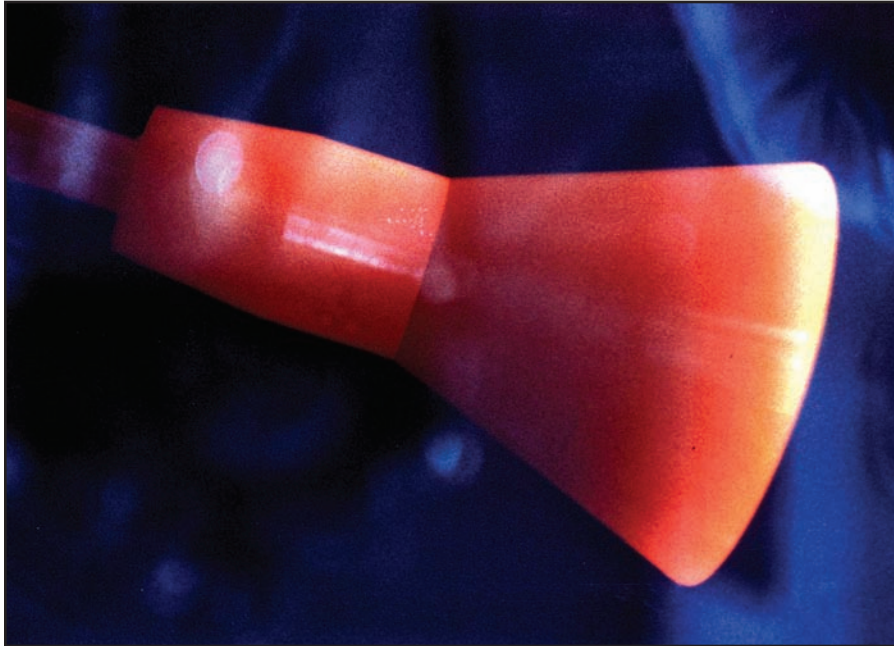
Approximately 5,842 “occupancy hours” are listed as Gemini support on the master log of test work conducted in four of the center’s five major test facilities. These tests included a wide variety of Gemini-related aerodynamic and propulsion tests.

Early investigations in such areas as Titan base heating, Titan II “fire-in-the-hole” staging and development of the Bell Agena rocket engine for the Gemini target docking vehicle provided information important to



The full-scale Gemini abort system was checked in J-1 in 1963. The tests helped determine a solution for retrorocket failures during a launch abort.

## Project Gemini



**A small model of the reentry configuration of the Gemini capsule glows red hot while immersed in a Mach 10 airflow. The model was subjected to the same conditions it would meet during reentry. The tests were aimed at providing data for the design of the heat shield.**

the Gemini development. Thus, the center's support for Gemini can be considered as beginning in the spring of 1959 when an early version of the Agena engine was first installed in the Engine Test Facility's (ETF) T-3 test cell.

Even the center's early work on the Atlas, used to launch the Gemini-Agena target vehicle, can be considered part of the center's contribution to the Gemini program.

During testing at AEDC, models of the Gemini space capsule were subjected to extreme reentry conditions in the hypersonic tunnels long before the first capsule was actually built. These tests dictated the design and structure of the capsule and the ablative shield that protects the astronauts from the fiery heat generated upon entering the atmosphere.

The same was true with the astronauts' escape systems, retrorockets and attitude controls. Each was developed and tested under the simulated conditions and environments in which it actually would have to operate.

The first environmental testing of the Agena began in March 1959. Since that time, AEDC did many thousands of hours of testing on the various Agena configurations, together with their satellite payloads.

A full-scale, dynamic stage-separation test was conducted for the first time in 1963 by simulating a Gemini Mode 2 Abort using the retro-rockets for stage separation and capsule escape during the boost phase of launch.

The test simulated spacecraft retro abort at an altitude of 70,000 feet by firing a full-scale spacecraft afterbody (consisting of a heat shield and retrograde rocket system on a rail-borne carriage). The retrograde section of the Gemini

adaptor section was separated from the equipment section by a linear-shaped charge and the retromotors accelerated the capsule system down the track. Spacecraft drag was simulated with a constant-force cylinder mechanism.

Further testing of the Gemini escape system was conducted in the Propulsion Wind Tunnel (PWT) facility. A test to determine the deployment, inflation and drag characteristics of a close-coupled ballute decelerator attached to a full-scale, rigid manikin was conducted in the 16-foot supersonic wind tunnel (16S). The ballute system was intended to stabilize and decelerate the astronaut prior to parachute deployment in the Gemini emergency

escape system. Deployments of the initial ballute configuration were unsuccessful. Various modifications were accomplished until two successful deployments were achieved. Drag levels for the configurations tested were now lower than required and no further modifications were necessary as determined by the contractor.

Another example of the center's contribution to the Gemini program was the top-priority testing of the Agena engine following failure of the target docking vehicle in the Gemini 6 mission in October 1964. Under a project called "Sure Fire," engineers and support personnel at the center worked around the clock to pinpoint the cause of that failure and to prove the reliability of "fixes" that



**The reentry model of the earth-orbiting, two-man Gemini was tested in many of the center's test units, including the 50-inch Mach 10 wind tunnel.**

had been made in the engine's fuel and electrical systems.

The Agena engine that would put a target vehicle into orbit for rendezvous with Gemini 8 on March 15, 1966, passed the last of its ignition reliability and mission simulation tests at AEDC. In a final test run that lasted 180 seconds at a simulated altitude of 352,000 feet, the engine performed perfectly.

A total of 28 first- and second-phase tests, carried out under various temperatures and simulated altitude conditions, were conducted under "Sure Fire." This program, initiated by the Air Force and NASA, was given top priority following the failure of the Agena engine on the Gemini 6 space shot. Reports listed a "hard start," which in turn had resulted from an ignition delay, as the most likely cause, with a resulting failure of the vehicle.

Fuel arriving in the thrust chamber in advance of the oxidizer – a fuel lead, as it is called – is now believed to have caused a delay in ignition of the hypergolic propellants when it occurs at extreme altitudes in excess of 200,000 feet. Thus, modifications were made to ensure an oxidizer lead. These modifications changed the Gemini Agena Target Vehicle (GATV) engine to a configuration as similar as possible to the Agena D propulsion system while still maintaining the capability for multiple restarts while providing for astronaut safety. The standard Agena D could

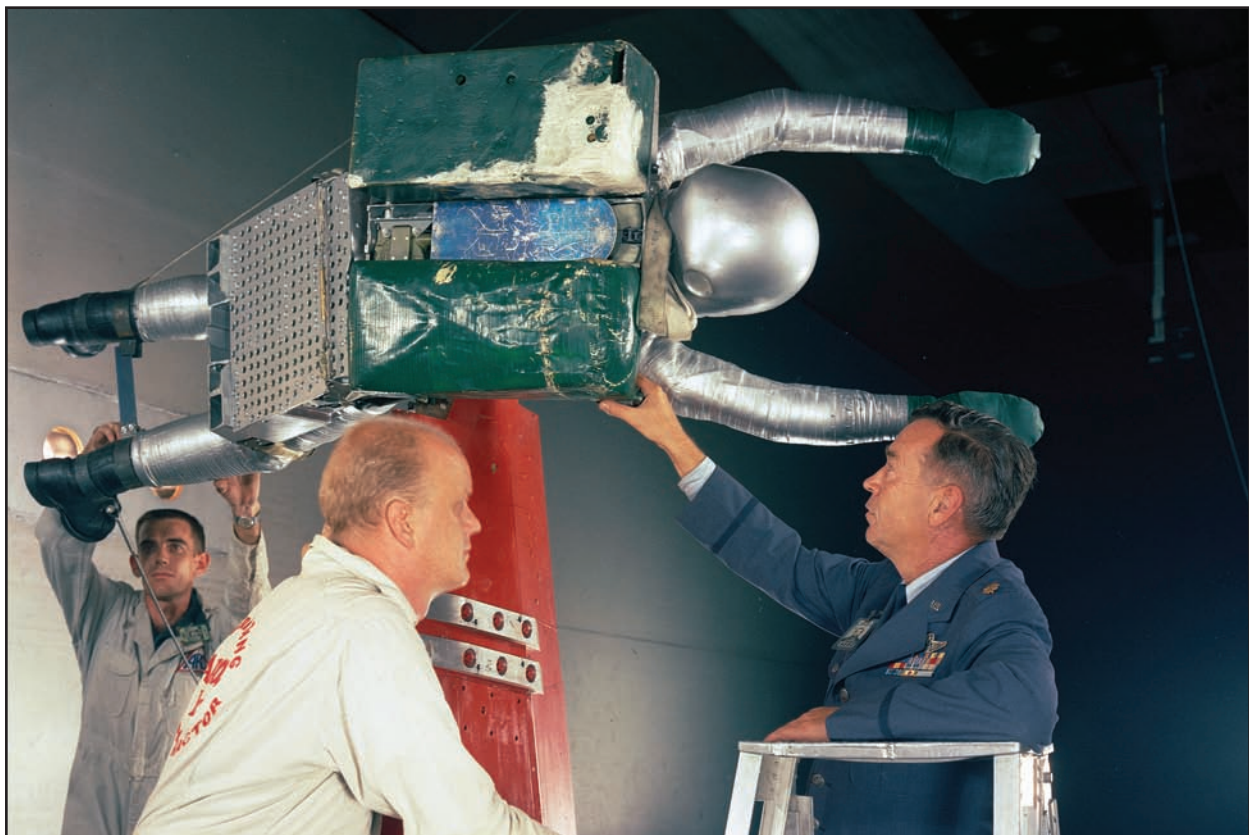
be restarted in space only twice.

The first test under the "Sure Fire" program was run at Arnold on Feb. 7, 1966. Five additional tests were successfully carried out over two days. Analysis of the data from the sixth firing indicated a need to make some minor adjustments on the engine. These included primarily replacement of the gas generator fuel valve and a change in the instrumentation lines.

A checkout firing at approximately 80,000 feet was started on Feb. 12, 1966. Countdown was initiated, and all systems functioned normally until the point of ignition, at which time the engine failed. A "hard start" caused the injector head to separate from the thrust chamber around the circumferential weld that joins the two.

After several other setbacks, the first of the 22 successful tests with the second Agena engine began at 6:55 a.m. on March 1, 1966. Then-AEDC commander Brig. Gen. Lee V. Gossick described the center's developmental support for the dozen highly successful flights of NASA's two-man spacecraft this way:

"The United States can be proud of its achievement in the Gemini program. There were minor difficulties, but the final tabulation stands at 12-for-12 – a perfect record that I'm sure was made possible to a large extent by the splendid test support provided by the Arnold Center."



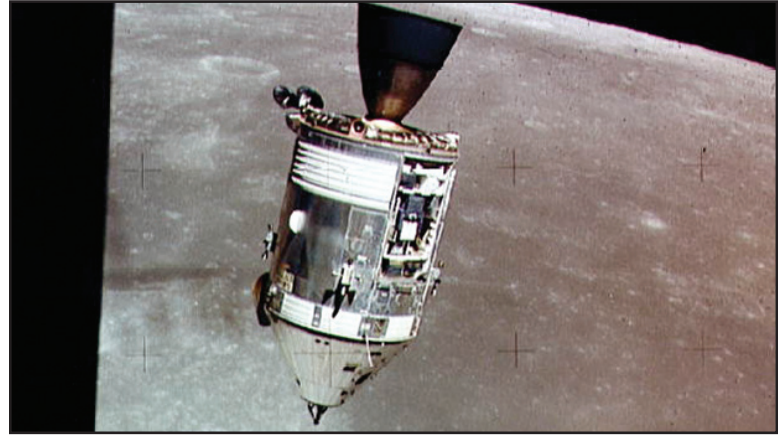
Parachute and survival packs come under scrutiny of AEDC engineers as they look over the Gemini Ballute undergoing testing in 16S in 1963.

# Project Apollo

*When Apollo 11 commander Neil Armstrong stepped out of the lunar module and took “one small step” in the Sea of Tranquility, calling it “one giant leap for mankind,” he fulfilled a dream as old as humanity. Project Apollo’s goals, which went beyond landing Americans on the Moon and returning them safely to Earth, included establishing the technology to meet other national interests in space; achieving preeminence in space; carrying out a program of scientific exploration of the Moon; and, developing man’s capability to work in the lunar environment. Six of the missions landed on the moon, where astronauts studied soil mechanics, meteoroids, seismic heat flow, lunar ranging, magnetic fields and solar wind. Apollos VII and IX tested spacecraft in Earth orbit; Apollo X orbited the moon as the dress rehearsal for the first landing.*

## Characteristics (Apollo Capsule)

**Crew:** Three  
**Crew Cabin Volume:** 6.17 m<sup>3</sup>  
**Length:** 3.47 m  
**Diameter:** 3.90 m  
**Mass:** 5,806 kg  
**Structure mass:** 1,567 kg  
**Heat shield mass:** 848 kg  
**RCS engine propellants:** 75 kg  
**Drinking water capacity:** 15 kg  
**Waste water capacity:** 26.5 kg  
**Atmosphere cleanser:** Lithium hydroxide  
**Odor absorber:** Activated charcoal  
Electric system batteries: three 40 ampere-hour silver zinc batteries and two 0.75 ampere-hour silver zinc pyrotechnic batteries  
**Parachutes:** Two 5-m conical ribbon drogue parachutes, three 2.2-m ringshot pilot parachutes, three 25.45-m ringsail main parachutes



## Highlights of Development Testing at AEDC

- **55,000 hours of test work in 25 different test facilities directly supporting the Apollo “man-on-the-moon” program, playing a crucial role in the nation’s development of space flight vehicles**
- **Firings of Saturn V upper-stage engine and lunar ascent/decent motors**

AEDC played a major role in man’s first landing on the moon in July 1969. From the first wind tunnel tests of a Saturn rocket model run in 1960 to more than 1,700 firings of the actual motors that made up the giant Saturn V launch vehicle in rocket test cells at simulated near-space conditions – AEDC was involved.

Just a little over nine years before Neil Armstrong’s famous, “one small step for man and one giant leap for mankind” comments, the first aerodynamic test had been run on a scale model of a proposed Saturn launch configuration on June 6, 1960.

From 1960 to 1968, a total of 3,300 wind tunnel test hours – more than 35 percent of all the NASA Apollo program wind tunnel work – was completed at AEDC. In all, 25 of AEDC’s 41 test facilities were involved in 55,000 hours of test work directly supporting the Apollo program.

In addition to determining flight characteristics of the launch configuration, tests conducted at AEDC provided data that helped NASA to program reentry parameters for the Apollo Command Module so that it would land within a mile or so of the recovery aircraft carrier. Reliability was proven for the launch abort/escape systems (which never had to be used), altitude start and operation of the Saturn IVB third stage, and the Service Propulsion System, which powered the Apollo Spacecraft.

The first wind tunnel tests of models of the Apollo spacecraft ran in June 1962, in the von Kármán Gas Dynamics Facility’s (VKF) 50-inch Mach 10 wind tunnel.

The first propulsion system test involved base heating studies on a proposed Saturn launch vehicle configuration in January 1961. Initial activity in support of the propulsion systems for the Apollo spacecraft modules involved an exploratory program using a 1/3-scale rocket engine.

The tests were run in a simulated space environment for the Service Module – the propulsion unit for the spacecraft that remained in orbit around the moon while two astronauts in the Lunar Excursion Module (LEM) explored the moon’s surface. Results of these tests helped NASA in selection of a thrust chamber assembly and also led to the selection of an optimum nozzle configuration. In August 1963, a series of tests started using the full-scale Service Module primary (rocket) propulsion system to flight-qualify this 21,000-pound-thrust engine for its lunar mission throughout the various possible firing cycles.

In May 1964, an accelerated development test program began on the 3,500-pound-thrust LEM ascent engine under simulated space conditions. The engine lifted the lunar vehicle off the moon to return the astronauts to the orbiting Service Module. This program evaluated the design of the thrust chamber; evaluated the prototype flight-weight engine to define ballistic performance and structural integrity; and simulated the launch of the LEM ascent stage from the descent stage on the lunar surface.

Preparation for development of the 10,000-pound-thrust LEM descent engine, which decelerated the two-man capsule to a soft landing on the moon, began in May 1965. AEDC also did extensive altitude testing of the reaction control (course correction) system motors for both the Service and Command Modules. This included, among other work, development of test techniques for firing these rocket motors at a simulated altitude of nearly 80 miles. Wind tunnel aerodynamic tests refined the Saturn V launch configuration. A wealth of data produced in these tests contributed immeasurably to the design of the Saturn V launch vehicle as well as the Apollo Spacecraft and its emergency abort capsule escape system. The overall



**A three-month test program examining the performance of several proposed improvements to the liquid-fueled transtage rocket motor was completed in the same test cell in which the original study was conducted.**



**AEDC engineers performed detailed tests on a number of facets of NASA’s Apollo program, including aerodynamic testing of this scale model of the Apollo three-man capsule with its escape tower in 1962. Later tests established the need for canard control surfaces at the apex of the escape rocket.**

test program at AEDC was designed by NASA to obtain data on aerodynamic heating, stability during reentry, reentry heat ablation, interaction between separating components during escape operations, and aerodynamic loading throughout the flight regime – as well as to help solve related problems that arose during development. The aerodynamic tests provided information that was critically important in solving hundreds of problems and tasks associated with Apollo spacecraft development.

The biggest Apollo tests conducted at the center were firings of the Saturn IVB engine in an altitude rocket test cell. The complete engine was fired at simulated altitude conditions of more than 100,000 feet. The Saturn IVB was the second stage of the smaller Saturn IB rocket, which was used on the first suborbital Apollo flights. It was also used as the third stage of the Saturn V. Five J-2 engines made up the second stage of the Saturn V. The J-2 engine in this stage generated 200,000 pounds of thrust, using liquid hydrogen and liquid oxygen as the propellant. The second stage was 22.75 feet in diameter, 58.5 feet tall and weighed 70 tons. The value of testing this engine in an altitude test cell was proven when an over-temperature problem developed that had not shown up in sea-level tests performed by the manufacturer. The cause of the problem was identified and corrected at AEDC, and the engine fired successfully under all probable starting conditions in subsequent tests and actual flights.

From May 1963 to June 1968, tests were run on the Service Propulsion Engine. Results helped confirm that the Apollo XVI mission flown by John Young, Charles Duke and Ken Mattingly could safely continue when a wobble in the engine was discovered in flight. Also tested were the four 5,000-pound-thrust retrorockets that ensured proper separation of the Saturn IVB stage from the Service Command and Lunar Excursion Modules, which continued on to the moon.

# STS

## Space Transportation System (Space Shuttle)

The space shuttle serves as America's current manned reusable launch vehicle with the capability of delivering and returning large payloads and scientific experiments to and from space. While in an emergency the shuttle can carry 11 astronauts, it usually carries five to seven.

The shuttle fleet is composed of the *Discovery*, *Atlantis* and *Endeavour*. The first orbiter, *Enterprise*, was used only for testing purposes. *Enterprise* was followed by four operational space shuttles: *Columbia*, *Challenger*, *Discovery* and *Atlantis*. *Challenger* was destroyed on launch in 1986. *Columbia* was destroyed on reentry in 2003. NASA announced in 2004 that the space shuttle will be retired in 2010 and replaced by the Orion/Ares space system.

### Characteristics (Orbital)

**Length:** 122.17 feet  
**Wingspan:** 78.06 feet  
**Height:** 58.58 feet  
**Empty Weight:** 151,205 pounds  
**Gross Liftoff Weight:** 240,000 pounds  
**Maximum Landing Weight:** 230,000 pounds  
**Main Engines:** Three Rocketdyne Block 2A SSMEs, each with a sea-level thrust of 393,800 lbs  
**Maximum Payload:** 55,250 pounds  
**Operational Altitude:** 100 to 520 nm  
**Maximum Speed:** 25,404 feet per second  
**Crew:** Seven

### (System Stack)

**Height:** 183.7 feet  
**Gross Liftoff Weight:** 4.5 million pounds  
**Total Liftoff Thrust:** 6.781 million pounds force



### Highlights of Development Testing at AEDC

- Evaluated various model configurations for the space shuttle program, obtaining data on heat transfer and aerodynamic forces and pressures, which helped to determine the appropriate construction materials and establish baseline flight models for the ascent portion of the mission
- Separation predictions for the two strap-on solid-propellant boosters from the shuttle after burnout
- Key role in NASA's Return to Flight program after the breakup of *Columbia* on reentry in February 2003

During the 1970s, NASA's emphasis shifted from deep space exploration to near-earth space operations and development, including the Space Transportation System (STS) known as the space shuttle.

AEDC evaluated various model configurations for the space shuttle program, obtaining data on heat transfer, aerodynamic forces and pressures.

These tests helped to determine the appropriate construction materials and to establish baseline flight models for the ascent and reentry portions of the mission. The tests also developed separation predictions for the two strap-on, solid-propellant boosters from the shuttle after burnout.

Space shuttle testing has been a major effort at AEDC since 1970.

The shuttle is composed of three principal elements: the manned vehicle called the orbiter; a large tank containing the orbiter's liquid fuel; and a pair of expendable, solid-propellant booster rockets to lift the orbiter and its fuel supply into space.

Today's design evolved from NASA's Apollo Application Program of the late 1960s, with the name "space shuttle" coming into use in 1968.

The first AEDC tests under the space shuttle name were conducted in late 1970 on a stage-and-a-half concept developed by Chrysler Corp., called the Single-Stage Earth Orbital Reusable Vehicle (SERV) in the Propulsion Wind Tunnel (PWT) facility's 16-foot transonic wind tunnel (16T), although primary design emphasis at the time was toward a fully reusable approach.

A Rockwell International (then North American Rockwell)

orbiter design was tested in early 1971, and about mid-year, an extended series of aerodynamic tests was conducted on the complete shuttle vehicles proposed by the two principal contending teams – McDonnell Douglas/Martin Marietta and North American Rockwell/General Dynamics.

In 1972, NASA announced a change in the basic structure of the shuttle, with the manned booster portion of the vehicle being replaced with a fuel tank and solid booster rockets. Later that year, Rockwell International was selected as the prime contractor for the shuttle program.

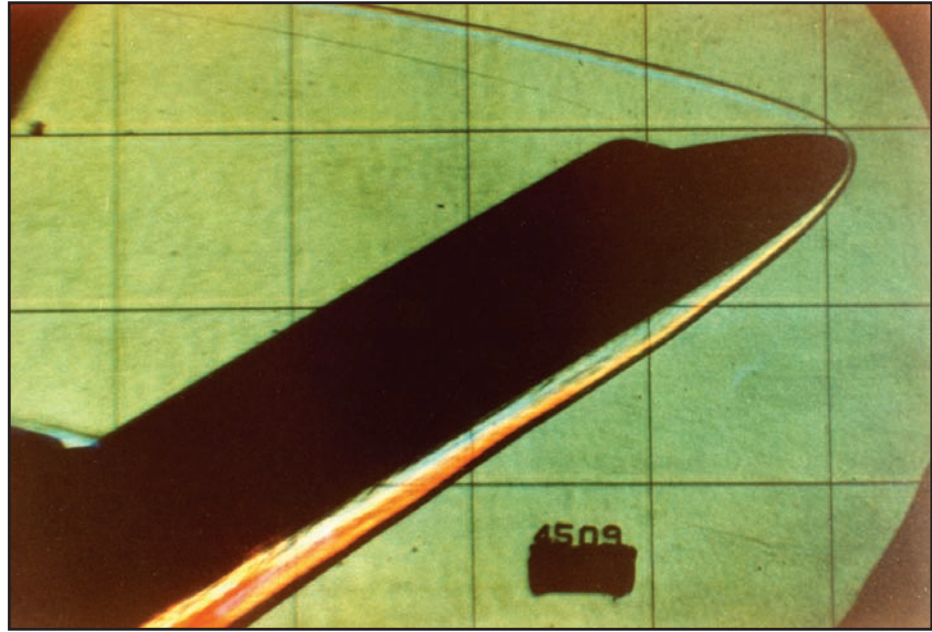
As noted above, in early 1971, a model of the orbiter vehicle for the space shuttle program was tested in the 4-foot transonic wind tunnel (4T) to obtain interference-free data and thus determine tunnel blockage effects the model would produce when tested subsequently in a 14-inch tunnel at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. This 0.0035-scale orbiter model was tested at Mach numbers from 0.4 to 1.3 at angles of attack from -4 to 77 degrees.

1972 was a busy year. In February, AEDC engineers were studying the effects of interacting exhaust plumes on the two stages of a fully reusable space shuttle, with a double model support system used to permit the position of the models to be changed at will. In addition, both models were equipped with variable-area compressed air nozzles which permitted the tailoring of the plumes to match each flight condition simulated.

Heat-sensitive paint permitted engineers to record heat buildup on the space shuttle configuration during wind tunnel tests.

Aerodynamic testing of a candidate space shuttle configuration included photographic study of the airflow around the booster and orbiter vehicles individually and in various mated positions. The models were mounted on a dual support to permit the tests to be conducted in a variety of flight stages, including ascent in mated position, separation at design conditions, reentry and abort separation under less than optimum conditions.

By the summer, one matter of interest to space shuttle designers was determining the pressures and temperatures the orbiter and booster would be subjected to through the



This Schlieren photograph of the North American Rockwell-General Dynamics design is an example of the photographic study of the airflow around the booster and orbiter vehicles in mated position.

interaction of their shock waves. A series of tests was conducted to measure temperatures and pressures for comparison with analytical results. After a series of tests using very simple forms to represent a booster paired with an orbiter, data were taken with the hypothetical orbiter-booster combination.

At the end of the 1972, the relationships between nose shape and heating and airflow behavior were the subject of tests on the manned portion of the space shuttle in the center's von Kármán Gas Dynamics Facility (VKF). Two interchangeable nose sections were used on the model to obtain data on differences in heat distribution and airflow characteristics. The model was subjected to simulated flight conditions at Mach 8 and altitudes of 120,000 to 150,000 feet.

When environmental concerns began to arise in 1973 in connection with the SST as to the kinds and quantities of chemical compounds they would emit, how these contaminants will disperse, and what their effect might be on the composition of the atmosphere, AEDC engineers were called upon to conduct tests under simulated SST operating conditions in 16T.

By the end of 1973, almost all hypersonic portions of a typical space shuttle flight had been sampled in wind tunnel tests at the center.

Segments of the flight profile simulated in the tests were separation of the orbiter (the manned portion of the shuttle) and its external fuel tank from the two large solid-propellant rocket motors that lift them into space; flight of the orbiter while coupled with its fuel tank and without it;

## Space Transportation System

and reentry of the orbiter into the earth's atmosphere.

Models of the Rockwell International vehicle ranging from one foot to more than two feet in length were used in the tests in four of the major wind tunnels of VKF.

Of particular interest were flight characteristics of the orbiter and heat levels that various segments of the system can be expected to encounter while traveling at speeds of four and a half to 20 times the speed of sound.

Accomplishing the test objectives required the application of a full range of techniques – temperature sensitive paint, models studded with temperature- and pressure-sensing devices, probes small enough to slide through the eye of a needle, simulation of the solid rocket booster (SRB) separation motor exhaust with compressed gases, chilling models to sub-zero temperatures with liquid nitrogen, a double support system that allows portions of the model to be moved by remote control, and simulation of insulating material planned to protect the orbiter.

Information produced in AEDC investigations into the heating problems involved in development of a shuttle have been described by a NASA official as contributing “significantly to the heat transfer for complex body shapes.”

### Lightweight Model

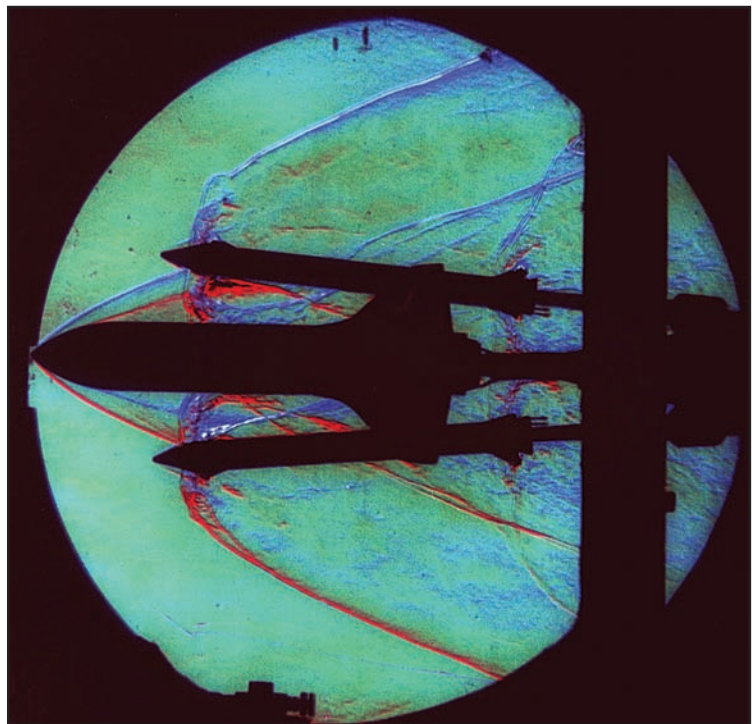
One of the smallest and lightest models of the Rockwell International space shuttle orbiter used in wind tunnel tests at AEDC was a foot long and weighed about a pound and a half. The hollow model was fabricated of magnesium. To further lighten the model, parallel slots were cut in the wings, filled with balsa wood and covered with an epoxy paint to provide a smooth surface. It was used to measure lift and drag of the orbiter at speeds of 16 and 20 times the speed of sound in one of the hypersonic tunnels of VKF.

### Shuttle Airflow

Airflow around the space shuttle orbiter model was



The scale model of the Space Transportation System (STS) is shown just before a staging test in hypersonic Tunnel A in the von Kármán Gas Dynamics Facility (VKF).



Space shuttle separation tests performed at AEDC examined dual solid-fuel booster separation from the shuttle and external tank. This Schlieren photograph shows a test in Supersonic Wind Tunnel A of the VKF in 1974.

revealed in Schlieren photographs. The model was positioned at a 30-degree angle of attack in an airflow



moving about 10 times the speed of sound.

### Tiny Probes For Shuttle Measurements

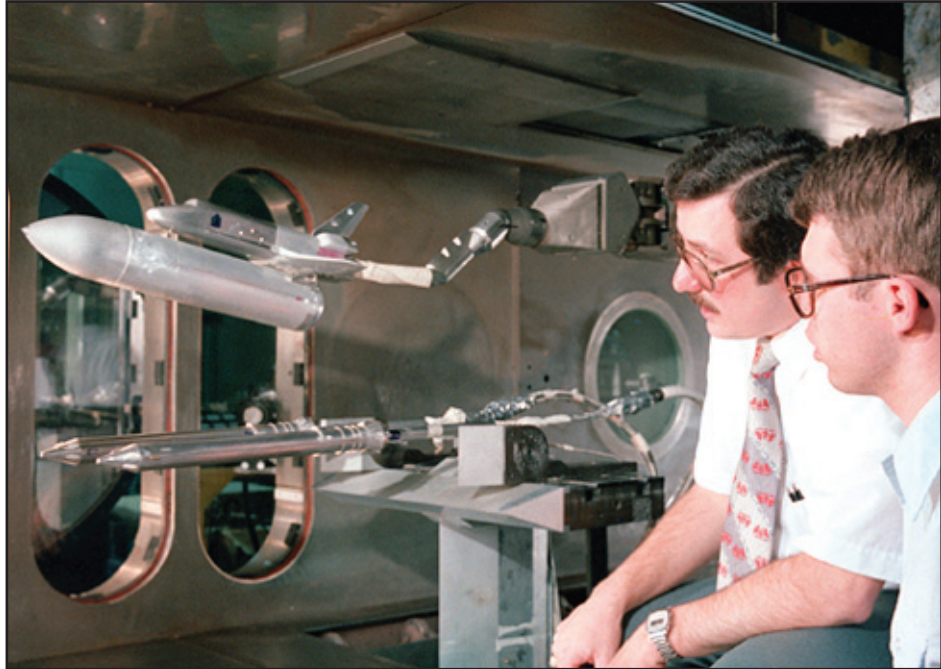
Miniature temperature and pressure probes with diameters measured in the thousandths of an inch were needed to sample airflow close to the surface of a space shuttle orbiter model during a test. The center probe of the three-pronged instrument was fabricated from hypodermic needle tubing with an inside diameter of 10 thousandths of an inch. The outside diameter tapered from 20 thousandths at its base to 14 thousandths at the tip. The two outside probes are for measuring temperature, one being 10 thousandths of an inch in diameter and the other 20 thousandths. Despite their small size, the probes withstood airspeeds of eight times the speed of sound in taking measurements in the very thin layer of air closest to the surface of the model.

In December 1973, in its first application – space shuttle staging tests for NASA – data that NASA estimated would have required 300 hours using more standard techniques were obtained in just 40 hours. The models used were about 18 inches long and 4 inches in diameter.

Projecting downward through the roof of the tunnel, the new support carried that part of the flight vehicle to be separated, while the parent portion of the model was mounted on the tunnel's standard support.

The computer controlling the movable portion of the model was programmed to position the model at various points of a 3-D grid and record aerodynamic forces on the model at those points. (Spacing of these data points within the grid need not be either symmetrical or uniform, and their spacing can be altered during the course of a test. Data points may also be omitted, if desired.) At each of the data points, the flight attitude of the model can be controlled to examine the effects of pitch, roll and yaw on the forces acting on the model. Data taken at each point are transformed in the computer into their most usable form and shifted to printout equipment while the computer directs the model to its next data point.

In addition to providing six-degrees-of-freedom for the model, the support also contains provision for the use of high-pressure gas to simulate rocket motor exhaust



**AEDC engineers examine a scaled model of the space shuttle undergoing aerodynamic testing. Engineers use computer-controlled auxiliary stings to duplicate separation trajectories.**

for staging studies. And since the support can be shifted from one wind tunnel to another, these studies could be performed at simulated flight speeds in excess of 3,000 miles an hour.

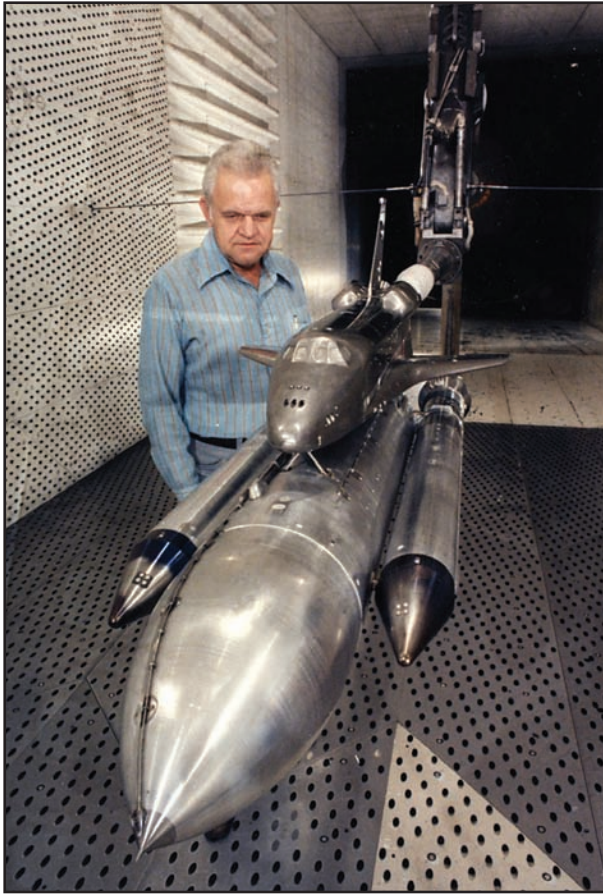
In 1974, tests to study space shuttle heating and aerodynamic forces during the ascent phase of its flight were conducted at 4.5 and 20 times the speed of sound in VKF.

For heating tests, considerably larger models of the orbiter and its external tank were used to look at the interactive heat between the two during the time interval from jettison of the spent solid booster rockets to jettison of the external liquid fuel tank just prior to entering orbit around the earth.

Another test series, also conducted in VKF, studied the effectiveness of the orbiter's control surfaces at various angles of attack at speeds of six, eight and 10 times the speed of sound.

Later in 1974, tests looking at the separation of the two space shuttle solid rocket boosters were completed. Exhaust from small separation motors located in the booster casings to force the expended rockets away from the orbiter was simulated using high-pressure air. A triple support was needed for the test: a support for the orbiter and its external fuel tank, and a movable arm for each of the two model solid boosters. The total system was pitched and rolled for attitude variations.

Schlieren photos showed the interactions between the separation motor exhaust and the airflow around the shuttle



**A 2-percent model of the shuttle orbiter, external fuel tank and solid rocket boosters is inspected prior to a test in 16T that measured aerodynamic forces acting on the total vehicle configuration.**

at 4.5 times the speed of sound.

The end of 1974 proved to be busy for space shuttle testing. In October, tests involved the heat that will accumulate on the nozzles of the orbiter's main engines during reentry into the earth's atmosphere. To create as little disturbance as possible to the Mach 8 airflow around the rear of the craft, testers mounted the model in an inverted position with the support taking the place of the craft's vertical control surface.

Also during October, aerodynamic tests investigating the interaction between the manned space shuttle orbiter and its large external fuel tank during jettison were completed. The tests were conducted at Mach 6 and 8 using 0.01-scale models and the center's new computer-controlled model support system. The computer not only recorded the forces acting upon the model but, while those data were being analyzed, moved the model to the next preselected test point. Data were produced in printed form within seconds, giving engineers essentially real-time information on test progress.

In November, AEDC became involved in shuttle testing using the largest and most detailed models ever installed

in its wind tunnels.

The 4-percent scale models represented the forward half of the manned portion of the shuttle and were used to study heat buildup during the critical reentry portion of the flight, when temperatures would reach their highest point. Temperature levels at other points on the orbiter's flight trajectory also were recorded during the tests which, extended throughout the remainder of the year.

Two different measuring techniques were used in the heating tests, and thus two kinds of models were required. Non-metallic models were used with phase-change paints – paints that change from solid to liquid at specific temperatures. The other model was one in which temperatures are measured through installation of thermocouples in the model's skin.

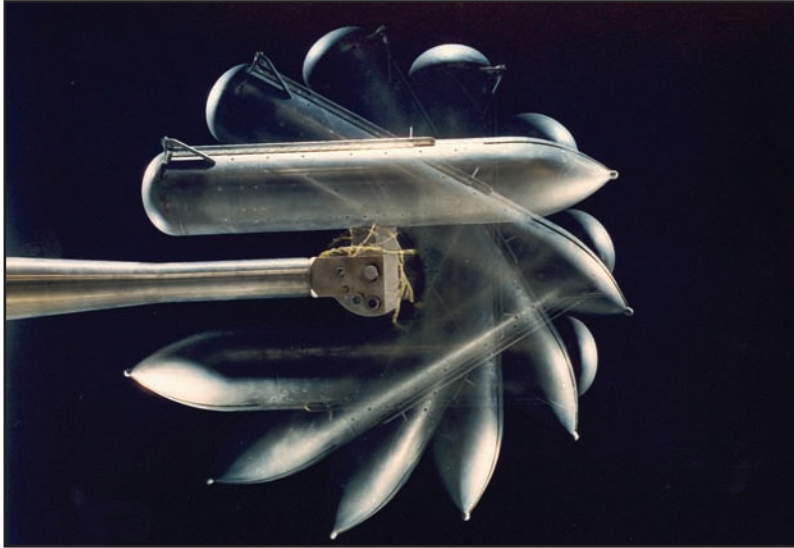
These models reflected the latest design details on the forward half of the orbiter, including windows, vents for various onboard systems, details of the cargo hatch and recessed nozzles of the small rocket motors that helped control the orbiter's flight path.

The 4-percent scale was the fourth model size to be tested in AEDC wind tunnels. Earlier tests used 0.01-scale, 1.5-percent and 1.75-percent scale models. These were used in the study of flight characteristics of the complete shuttle configuration as well as in the study of the individual components; heat buildup on the various components, or specific sections of these components; and in the mutual interactions between the components as they separate at different points in the flight profile.

Space shuttle propellant testing for NASA quite literally went underground at AEDC in May of 1975. These tests were part of a selection process by the space agency to find a compatible propellant for the auxiliary motors that would cause separation between the space shuttle's manned orbiter and the two large solid booster rockets that will lift it into space. The studies were conducted 175 feet below ground at an intermediate level of the center's 250-foot-deep vertical rocket motor test cell.

It was originally proposed that small solid-rocket motors be used to provide the thrust needed to push the expanded boosters away from the orbiter and its external fuel tank. However, feasibility tests conducted at AEDC using surplus Apollo motors indicated that the hot exhaust gases from this particular motor would have adverse effects on the thermal protection materials on the orbiter and fuel tank. This precipitated the search for a more compatible propellant.

Three candidate propellants were examined at a simulated altitude of 130,000 feet. Reusable ballistic test evaluation system (BATES) motors were loaded with 100 pounds of the candidate propellant and a charge that burned in two seconds to impinge on six-by-six inch tiles of thermal protection material at various distances and orientations. Material samples included both "carbon



**Tumbling reentry heat loads on the space shuttle tank were measured on a scale model in 1974. The model was rotated longitudinally in test conditions simulating flight at 5,500 mph.**

carbon” material to be used on those portions of the orbiter subjected to the highest temperatures – up to 3,000 degrees Fahrenheit – and high-temperature reusable surface insulation (HRSI) material to protect the orbiter at temperatures up to 2,300 degrees Fahrenheit, as well as the cellular-type insulation to be applied to the external fuel tank.

Of principal interest were erosion effects on the surface and edges of the material samples. Collection devices were also installed to gather particle samples at various points in the rocket plume.

Pressure and temperature measurements were taken in the rocket plumes, and surface temperatures and heating rates were taken on selected material samples. Data and samples were returned to MSFC after each firing for detailed analysis.

The test program involved a total of seven firings of the reloadable motors. They were fired singly or in pairs, and as many as 21 material samples were used in a single firing.

In that same month (May 1975), aerodynamic tests on a model of the latest space shuttle orbiter configuration were completed in two of AEDC’s supersonic wind tunnels. The most noticeable differences in the model, compared with earlier versions, were changes in shape of the Orbiter Maneuvering System (OMS) pods. Effectiveness of the control surfaces was measured at simulated flight speeds ranging from two to eight times the speed of sound (Mach 2 to 8) and at angles of attack from -3 degrees to 45 degrees.

In June 1975, a technique similar to those

used to convert aerial photographs to contour maps was applied in wind tunnel testing at AEDC.

The approach was developed by contractor personnel and was first used in a study of physical behavior under simulated flight conditions of a spray-on insulating material proposed for use on the space shuttle’s external fuel tank.

Requirements for the test, conducted in VKF, were out of the ordinary in that this was the first material evaluation study of its kind to be done in the facility. One test objective was a pictorial history of the material’s behavior during the ascent portion of a space shuttle flight.

The first step in the measurement process, as put together by VKF’s Aerodynamics Instrumentation Branch, was to photograph an array of parallel lines onto high-contrast film. This pattern was then projected at an angle onto the surface of the material sample in the wind tunnel.

Prior to testing, a series of photographs were taken from directly overhead with the sample positioned at the same relative angles at which data was taken during the test. These were processed, converted to positives, and held for later use.

During the actual test, the same pattern was projected onto the material surface. The overhead camera was keyed to the data-taking process so that each time data were taken a still photograph also was made. As the surface of the material changed contour, the projected lines became misshapen, like the shadow of a bridge crossing the uneven valley below.



**A NASA space shuttle orbiter model was tested in 1978 in tunnel 16T. This series of tests provided data on the effects of vertical stabilizer deformation on flight control.**



Foam insulation for the external fuel tank of NASA's space shuttle underwent material testing in VKF's hypersonic Tunnel C.

After the test, the negatives were matched with a corresponding positive and printed together. The result was a series of white bars across the photograph, indicating where the undistorted surface was and corresponding black lines indicating the position of the surface at the time the photograph was taken.

Through standard photogrammetric approaches, the amount of recession could be measured within the tolerances required for successful analysis of test results.

One of the most highly detailed and highly instrumented models of the NASA space shuttle ever constructed was used for the first time in wind tunnel tests at AEDC in November 1975.

The model represented the entire shuttle at launch—the manned orbiter, its large external fuel tank, and the two solid-propellant booster rockets. The orbiter had a 16.5-inch wingspan, and the external fuel tank was 32 inches long and 5-3/4 inches in diameter.

Spread throughout the model were 835 temperature-sensing devices, nearly three times the number of thermocouples normally installed in similar wind tunnel models tested at AEDC at that time. They were used to record heat levels on all three components of the shuttle at flight conditions simulating those at which the expended solid boosters would be jettisoned during the ascent phase of the shuttle's flight.

Two other shuttle-related tests were also completed, one to examine aerodynamic forces on the vehicle during separation of the expended solid boosters and the other to



**A series of tests was completed in 1975 to determine heat levels the space shuttle's manned orbiter would encounter while operating at a high angle of attack. The tests were conducted at simulated flight speeds of eight times the speed of sound. Special paints that change from a solid to liquid at specific temperatures were used to record temperature levels, and surface-applied oils recorded airflow over the surface of the vehicle.**

examine heat levels on the orbiter when flying alone at a high angle of attack.

The separation study was done with a smaller-scale model using a computer-controlled support system. The orbiter and external fuel tank models were installed on the wind tunnel's standard support system, and a model of one of the solid boosters was attached to the computer-

controlled support.

Not only were measurements recorded with the single booster model at various points beside, below and behind the orbiter-tank combination, but measurements were also made with the booster and orbiter-tank at pitch and yaw angles.

In the third test, heating data were obtained on an orbiter model positioned at a high angle of attack at a simulated flight speed eight times the speed of sound. Special paints that change from a solid to a liquid at specified temperatures were used

to record heating histories on the surface of the model. Oil-coating techniques were also used to examine airflow over the model.

Answering even apparently simple questions about flight systems that did not yet exist – such as the space shuttle – was to be a complex business.

For example, in September 1975, a “non-normal” effort was undertaken in the VKF’s 12-foot space chamber (12V). The initial objective was deceptively simple: to determine the physical and chemical composition of the exhaust generated during space shuttle launches, with particular attention to hydrogen chloride.

The AEDC effort was part of an extensive NASA program, involving many of the nation’s leading scientists, to ensure that space shuttle operations would not create any air quality or environmental problems.

The AEDC study involved essentially three phases: demonstrating that rocket firings can be accurately simulated in a closed chamber, designing the experimental hardware to obtain the necessary data; and then post-firing, analyzing the data. The test was a sizable undertaking because there were so many unknowns.

One of the last tests in 1975 was a study supporting the design of the pressure probe that is the heart of the manned orbiter’s velocity-measuring equipment.

By 1976, AEDC engineers were studying a shuttle abort sequence for the ascent phase, along with conducting tests to measure the effects of combustion temperature and metal content in the propellant on the pressures and circulation around the model base. In addition, a new nose shape for the shuttle’s external fuel tank was tested. Also,



**A 0.0175-percent scale model of NASA’s space shuttle orbiter, solid rocket booster and external fuel tanks underwent aerodynamic testing in tunnel 16T.**

at this time, European medical equipment was applied to the visualization of heating patterns on the surface of the shuttle’s orbiter vehicle under simulated flight conditions using infrared scanning. Tests to examine the insulating qualities and structural integrity of four proposed materials were conducted, and shuttle separation studies of two spent solid rocket boosters were completed.

Shuttle heating studies designed to measure effects on the windward surface of the space shuttle were completed in 1977. Also, wind tunnel tests were performed to examine the sound pressure levels generated around the base of the shuttle’s reusable solid rocket boosters as they fall back to the Earth. Finally, tests were completed to measure aerodynamic forces acting on the total vehicle configuration.

Air pressures and loads the space shuttle experiences during launch were mapped and measured on the most detailed models of 1978. Also, the shuttle orbiter hardware was studied with wind tunnel tests verifying that changes in the nose shape of the external tank on the shuttle wouldn’t cause unacceptably high temperatures during the ascent into space.

The first large developmental rocket motor for the Air Force’s Inertial Upper Stage (IUS) space vehicle was successfully tested in 1979. The IUS vehicle was being developed for the U. S. Air Force’s Space Division by Boeing Aerospace. It was designed to be a key element of the space shuttle program. Large and small basic rocket motors developed by United Technologies’ Chemical Systems Division can be combined in different numbers and configurations to power the IUS vehicle for orbital



**A 2.25-percent scale model of NASA's space shuttle launch vehicle is shown during hot rocket plume simulation tests in 16T. Aerodynamic effects generated by selected orbiter main engine-out configurations were determined. Exhaust from the orbiter main engines was simulated by short-duration burn of gaseous hydrogen and oxygen. Solid rocket booster (SRB) plumes were generated by burning a mixture of gases designed to match thermal and propulsive properties of the actual SRB plumes.**

transfer of payloads from the space shuttle to higher orbits and for deeper space missions. The purpose of the tests was to evaluate motor performance with the Thrust Vector Control (TVC) system, which steers the IUS in space, and to test two new insulation materials for use between the rocket case and the propellant.

Additional testing included calibrating the shuttle's Ascent Air Data System, which transmits information on the attitude of the entire launch vehicle.

Wind tunnel tests performed in 1980 helped NASA verify that a key component of the shuttle's launch vehicle would safely withstand the most severe aerodynamic conditions expected during the launch and ascent phase. Also, a developmental rocket motor designed for the IUS space vehicle was test fired with both a carbon-carbon Extendable Exit Cone (EEC) for greater thrust and a Thrust Vector Control System (TVCS) for gimbaling the

exhaust cone.

A year later, tests were performed in an AEDC wind tunnel to measure aerodynamic pressures on the Thermal Protection System (TPS) tiles on the shuttle orbiter in support of its scheduled launch for the spring of 1981. Data were obtained to make modifications that improved the integrity of the bonded attachment of the tiles to the orbiter.

Next, a wind tunnel test simulating separation of the shuttle's solid rocket boosters was conducted in preparation for the scheduled June 27, 1982, launch. This test provided NASA's Johnson Space Center with an expanded database and reduced overall data uncertainty for trajectory analysis of nominal and off-nominal flight paths in support of future shuttle flights. In addition, both small and large versions of solid-propellant rocket motors for the IUS space vehicle were tested to qualify the design of the propulsion system, which were used primarily with the shuttle to lift payloads weighing up to 5,000 pounds to higher orbits from the shuttle's low earth orbit.

A new technique in materials testing to examine the actual aerothermal conditions around protuberance areas where high heat loads occur allowed NASA to test 29 materials samples at AEDC in 1983. The samples were subjected to 1,440-degree Fahrenheit temperatures. Results allowed NASA to optimize the type and thickness of insulation used in critical protuberance areas on the external fuel tank. AEDC also tested an IUS, designated the Improved Performance Space Motor (IPSM), the first of the developmental solid-propellant rocket motors designed to be a kick motor for interplanetary voyages and to place spacecraft in stationary orbit approximately 22,000 miles from earth.

In order to determine how portions of the orbiter surface insulation were damaged during a voyage of the space shuttle, engineers at AEDC recreated the flight conditions in a wind tunnel to see whether the failure of the quilted Advanced Flexible Reusable Surface Insulation (AFRSI) could be duplicated. A 1984 re-enactment helped NASA to devise a more durable insulation layer for this region in future shuttle flights. The test objective was to establish the operational limits of the AFRSI by evaluating the material's response to combined aerothermodynamics and aero-acoustic environments simulating actual flight conditions. As a result of the testing, NASA added a thin ceramic coating to the insulation to ensure better performance.

A new thermal protection coating designed to protect the joints of the SRBs was evaluated at the center in 1988. Samples were examined for structural integrity and ablation for periods of up to three minutes. In addition, a pair of IUS motors that were scheduled to launch a satellite completed checkout at AEDC.

Phase I of a two-phase test to determine the aerothermal environment around protuberances on the SRBs was completed at AEDC in Tunnel C of VKF.

The effect of a space shuttle main engine (SSME) failure on the shuttle's aerodynamic loads during the initial stages of ascent were studied in wind tunnel tests, and a database was created for predicting the performance of the shuttle at various points in the trajectory should any one or two of the three orbiter engines fail.

Wind tunnel tests in 1989 helped NASA refine methods used to predict the altitude at which the breakup of the space shuttle external tanks occurs after separation from the orbiter.

Scientists at AEDC developed a device in 1990 for use in ground testing to observe the exhaust plume of the SSME to provide advance warning of performance defects and to initiate engine shutdown before a failure might occur.

At the request of NASA, AEDC developed the Optical Plume Anomaly Detector (OPAD) to monitor the health of the SSME at the MSFC Technology Test Bed during the SSME developmental ground testing.

In the process of reviewing films of engine failures occurring during SSME developmental testing, indicators of various abnormal events were seen. In eight of 27 failures, a visible occurrence that varied from a flash to extreme streaking in the plume was plainly obvious only milliseconds prior to engine failure. Investigators supposed that if a plainly visible event occurred, perhaps the onset of the visible event was gradual enough to detect inconsistent luminosity, or signals, below the visible threshold of the human eye. This led to this concept of a monitoring device to detect such events.

In late 1991, space shuttle tiles, which in the past had undergone extensive materials testing in AEDC wind tunnels, were back at the center – this time for measurements to determine the effects of space flight on the reflective characteristics of individual tiles.

Tests to provide thermal radiative property data were requested by the Phillips Lab, formerly the Geophysics Lab, at Hanscom Air Force Base (AFB), Massachusetts, to assist with their studies of shuttle tiles in flight. The Phillips Lab uses infrared cameras located on a Maui, Hawaii, mountaintop to observe the condition and measure



**Test personnel check out a model of the space shuttle with fuel tank and solid rocket motors in 16T prior to a test in 1988.**

the temperature of the tiles in flight.

Unfortunately, the tile temperatures can only be determined if the reflecting and energy-emitting properties of the tiles are known. That's where AEDC came in. The tiles were tested in the center's Bidirectional Reflectance Distribution Function (BDRF) measurements laboratory.

AEDC engineers were providing nontypical test data for NASA in 1992 when they conducted tests to help NASA scientists find an alternative to Freon as a blowing agent for the insulation on the external tank of the space shuttle. Freon had been used to manufacture the foam insulation on the space shuttle external tank since the shuttle program began, but since it had been identified as a cause of ozone depletion, Freon could no longer be used.

The test in AEDC's aerothermal wind tunnel provided data used to evaluate the effects of an aerothermal environment on samples of thermal insulation formed using new blowing agents. This test provided NASA engineers with information to select an alternate blowing agent to use in making the insulation on future space shuttle missions.

Extreme heat and speed were simulated in the tunnel to duplicate the conditions the thermal insulation on the external tank must withstand during launch. Each material sample was placed on a test wedge and instrumented with high-temperature gages to define the surface heating. By 1999, AEDC was assisting NASA with improvements in existing space shuttle materials.

According to NASA, during several previous space shuttle flights, including the shuttle launched on Nov. 29,



NASA personnel examine a shuttle model to be tested in AEDC's tunnel 16T.

1988, the shuttle external tank experienced a significant loss of foam from the intertank. The material lost caused damage to the thermal protection high-temperature tiles on the lower surface of the shuttle orbiter. The loss of external tank foam material and subsequent damage to reentry tiles was a concern because it caused tile replacement costs to significantly increase. As a result, NASA-MSFC selected AEDC to perform flight hardware materials tests on the shuttle's external tank panels in the VKF's supersonic Tunnel A. The purpose was to establish the cause of failure for the tank thermal protection materials at specified simulated flight conditions.

The Lockheed Martin manufactured non-reusable external tank, the largest element of the space shuttle, fuels the shuttle orbiter during powered flight and is comprised of three components: a liquid oxygen tank, a liquid hydrogen tank and an intertank assembly that connects the two propellant tanks. At the full capacity of 528,600 gallons of propellant, the external tank weighs 1.6 million pounds. The tank is covered with multi-layered, spray-on foam insulation that provides thermal insulation for the tank against the extreme internal and external temperatures generated during prelaunch, launch and flight.

Because the foam system is exposed to multiple forces acting on it, determining the actual cause of failure of the thermal protection system is difficult. The environmental factors include thermal protection system cell expansion,

aerodynamic loading, highly variable local flow conditions, oscillating shocks, vibration, temperature and main external tank substrate flexure.

Although NASA and other facilities had performed a number of tests in an attempt to define the underlying root cause of this foam loss, they had not been successful. At one time, the center's 4T and 16T wind tunnels were possibilities for the test, but Tunnel A's ability to closely duplicate flight conditions and control both ambient pressure and test sample immersion time made it the facility of choice.

Although the AEDC Tunnel A tests did not replicate the in-flight failures, they did provide detailed measurements to improve understanding of the flight environment and that fundamental failure mode. From these tests, NASA determined the failure was caused principally by foam cell expansion attributable to external heating at approximately Mach 4 combined with pressure change and aerodynamic shear. Specialized miniature shear gages and other instrumentation were installed during the test to measure these forces.

### **"Return-to-Flight"**

AEDC played an important role in supporting NASA's space shuttle Return-to-Flight program, which culminated with the launch of space shuttle *Discovery* in 2005.

Following the break up of *Columbia* during reentry in



February 2003, AEDC facilities and personnel experienced in manned space program testing responded to help NASA return to manned space flight. Return-to-Flight tests were conducted in five of AEDC's 58 testing facilities.

### Wind Tunnel Testing

The first of three series of wind tunnel tests occurred in June 2003 in AEDC's Tunnel A. These tests demonstrated the aerodynamic capabilities of some space shuttle redesign initiatives and provided valuable data on the aerodynamic heating caused by the new design during ascent.

Mounting an AEDC-designed and fabricated 100-percent scale metal model of the bipod ramp that connects the space shuttle to the main external fuel tank near the shuttle's nose in the tunnel, test personnel generated an environment similar to that encountered at various launches to orbit to observe the aerodynamic flow conditions.

The second series of tests began in 4T in August 2003. There, test crews measured the air pressure on models of the same bipod and ramp and a redesigned bipod area by placing pressure sensors in the models.

Heaters embedded into the insulation foam models prevented ice formation on the exposed metal components during tests and allowed the predicted flight structural thermal profile to be very accurately simulated.

Then, AEDC fabricated a new wind tunnel side wall that integrated model features with the test facility to more closely match the flight airflow conditions in the bipod area.

Another series of tests was conducted in the center's hypersonic Tunnel C. During this series, an AEDC-designed and -fabricated 30-percent scale redesigned bipod model was used to collect the heating rates and pressure measurements from locations distributed around the redesigned bipod attachment fitting and surrounding insulation foam.

### Foam Impact Testing

Engineers and test operators in AEDC's S-3 Ballistic Impact Range launched hundreds of projectiles made of the insulating foam material used on the shuttle's external tank. These "shots" simulated pieces of external tank foam



A "blue light" multiple exposure photo of the "full stack" space shuttle in the 16T wind tunnel.

breaking away from the tank during flight, as happened to *Columbia*, and striking various parts of the space shuttle such as the SRB.

The blocks were launched at various velocities and angles to simulate the different ways in which foam might strike the SRBs. These tests helped determine the effects of foam impact and provided information on the rocket booster's ability to withstand those impacts.

During each shot, high-pressure helium gas launched the foam projectiles at speeds from 150 to 2,255 feet per second down an 86-foot long rectangular barrel.

The targets included the struts connecting the solid-fueled rocket booster and external fuel tank, core panels representative of the thermal protection system materials and cover material for the range safety system antennae that would be used to abort a mission if sufficient damage occurred to the shuttle.

High-speed video cameras operating at speeds up to 20,000 frames per second documented the impacts and provided a means for measuring the velocity of the projectiles. Instrumentation on the target's panels acquired data at 50,000 samples per second to provide information on the stresses the targets sustained during the impact.

## Space Transportation System



A foam projectile is loaded into the 86-foot-long rectangular barrel of the center's Bird Impact Range in preparation for tests for the space shuttle "Return-to-Flight" program.



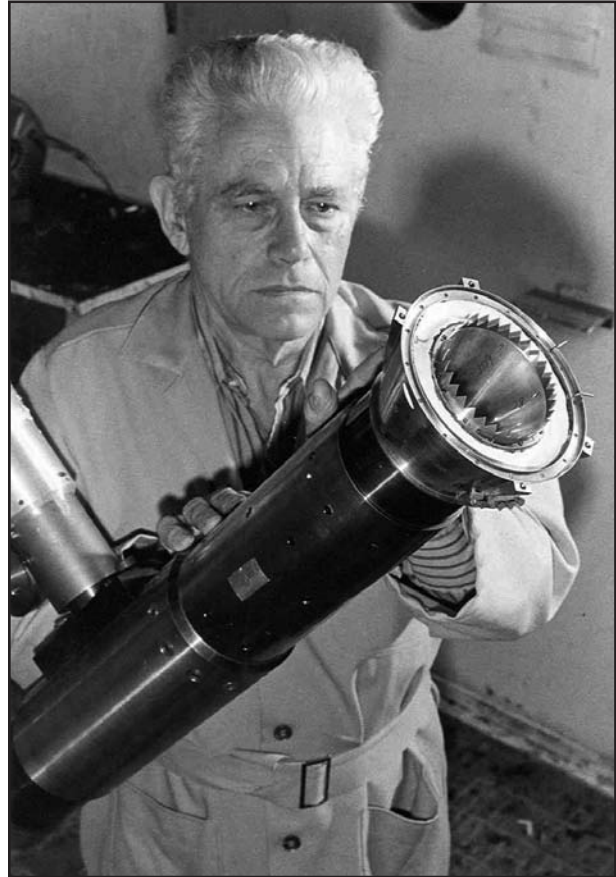
NASA test engineers examine a section of foam paneling of the type used on the space shuttle's main exterior fuel tank during liftoff. Tests on the panels were performed in Tunnel C as a part of NASA's "Return-to-Flight" program. The foam panel was exposed to temperatures above 1,400 degrees Fahrenheit at Mach 4.

### "Full-stack" Testing

AEDC completed a week of testing on a 3-percent scale "full stack" model in 16T in October 2004. The "full stack" model represents a space shuttle configuration similar to the vehicle at launch, with the external fuel tanks attached.

The objective of the test was to perform detailed pressure and force measurements and flow visualization on the shuttle model, particularly in the bipod area. The model was subjected to speeds ranging from those encountered just after takeoff to Mach 1.5.

Pressure sensitive paint (PSP) flow visualization was used to determine pressure data over the entire surface of the shuttle model as it was tested. This specialized paint fluoresces, or glows, under certain lighting, with brighter areas indicating lower pressure and dimmer areas indicating higher pressure. The paint is applied to the model, which is



AEDC completed a series of wind tunnel tests that examined the sound pressure levels that will be generated around the base of the space shuttle's reusable solid rocket boosters as they fall back to earth following the shuttle launch. Of particular interest was their effect on various instrument and control packages located in the rear of the booster and their effect on the overall booster structure. A total of 33 microphones were installed in the model to record sound levels as the model was rotated through a 90-degree angle-of-attack range, representing the tumbling motion the booster will go through after being jettisoned by the shuttle.

then imaged with digital cameras while the wind tunnel is operating. The images are processed through a program in a supercomputer to show the varying pressures in different colors. The team acquired pressure data on the two versions of external tanks, including the newer super lightweight tank and the older, standard-weight tank that dates to the late 1970s to compare aerodynamic performance.

During the force phase of the test, parts of the liquid-oxygen fuel system were installed onto small balances. Forces on these components were measured over a range of simulated flight conditions and model attitudes, including the roll maneuver that occurs shortly after take-off. NASA used the AEDC PSP flow visualization data to validate the Computational Fluid Dynamics data it generated in analyses at NASA facilities.

# GPS

## Global Positioning System

*The Global Positioning System (GPS) is a space-based radionavigation system that provides reliable positioning, navigation and timing services to military and civilian users on a continuous, worldwide basis. The GPS is made up of three parts: satellites orbiting the Earth; control and monitoring stations on Earth; and the GPS receivers owned by users. GPS satellites broadcast signals from space that are picked up and identified by GPS receivers. Each GPS receiver then provides a 3-D location plus the time.*

### Characteristics

**Primary Function:** World-wide positioning, navigation information  
**Contractors:** Block II/IIA, Rockwell International (Boeing North American); Block IIR, Lockheed Martin; Block IIR-M, Lockheed Martin; Block IIF, Boeing North American  
**Power Plant:** Solar panels generating 800 watts; Block IIF panels generate 2,450 watts  
**Weight:** Block IIA, 3,670 pounds; Block IIR-M, 4,480 pounds; Block IIF, 3,758 pounds  
**Height:** Block IIA, 136 inches; Block IIR, 70 inches; Block IIF, 98 inches  
**Width (includes wingspan):** Block IIA, 208.6 inches; Block IIR, 449 inches; Block IIF, about 116 feet  
**Design Life:** Block II/IIA, 7.5 years; Block IIR, 10 years; Block IIR-M (modernized) 8.57 years; Block IIF, 11 years  
**Date of First Launch:** 1978  
**Launch Vehicle:** Delta II; EELV for Block IIF  
**Date Constellation Fully Operational:** April 1995



### Highlights of Development Testing at AEDC

- **Development of the navigation network, tested both the Block I and II NAVSTAR Global Positioning System (GPS) satellites**
- **Validation of the GPS performance in a space environment in tests under vacuum conditions lasting up to 45 days**

Final acceptance and qualification tests of the NAVSTAR Global Positioning System (GPS) for a first launch in the fall of 1977 took place at AEDC during that same year.

The tests constituted a complete examination of all the operational subsystems aboard the satellite with the exception of the rocket motor that will position it in orbit. Primary program objectives for the work at AEDC were certification of the satellite's thermal control system, verification of the vehicle's operational systems and identification of any potential defects.

The first segment of the GPS test program was concerned primarily with validating the satellite's ability to keep its temperature-sensitive components within specified ranges both during a normal flight profile and in an emergency situation involving loss of electrical power from its solar cells.

The second segment focused on the stability of the satellite's rubidium clocks when subjected to temperature extremes. Clock accuracy in spacing the coded navigational signal is the heart of the satellite's operation, and the rubidium clocks are estimated to be accurate within one second in 30,000 years.

Finally, an extended test period was devoted to putting the satellite through six hot-cold cycles to temperatures at both extremes that exceeded acceptance temperatures. Besides the primary test objectives, the effort also produced actual performance values to compare against theoretical values that had been developed by Rockwell International.

In the mid-1980s, AEDC personnel performed thermal qualification and engineering design tests on a prototype of the Block II NAVSTAR GPS satellite. In the center's space chamber, normal temperature and vacuum conditions were simulated, as well as worst-case thermal temperatures the satellite might encounter. The prototype endured more than 1,000 hours – or 45 days – at vacuum conditions, providing critical test results for the satellites, which provide 3-D positioning information (longitude, latitude and altitude) within 10 meters for any spot on Earth.

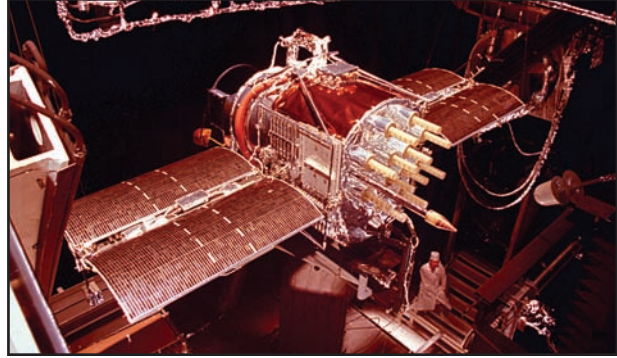
Daily tests were completed for four months in 1985, and these concluded the thermal qualification testing of the Block II NAVSTAR



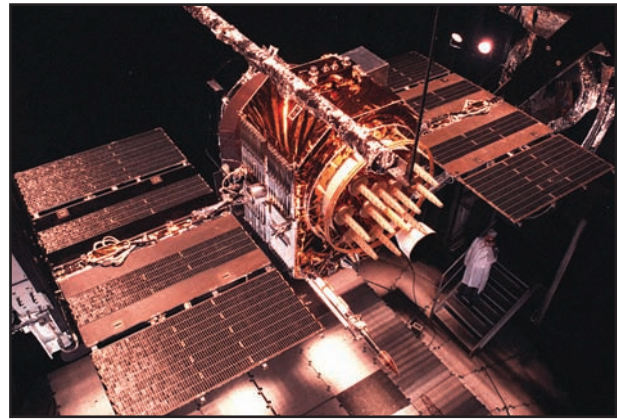
With installation complete and protective plastic wrapping removed, AEDC personnel take a close look at the stowed solar array panels that provide electricity for the NAVSTAR GPS satellite.

GPS satellite. The 4,000-pound Qualification Test Vehicle, a smaller prototype of the satellite, was lowered by crane into the 82-by-42 foot Mark I Space Simulation Chamber, which is equipped with an overhead solar simulator made up of five hundred, 1,000-watt lamps. A new record was set during the successful testing when the large chamber was held at vacuum conditions for 1,027 hours – 45 days straight – surpassing the previous record of 28 days. The satellite was spun at three revolutions per minute to measure thermal balance in a simulated transfer orbit – the elliptical orbit initially taken by the satellite following its release from the shuttle’s cargo bay. The vehicle’s solar panels were also deployed to their full 19-foot span during testing.

In 1986, critical satellite components needed additional protection from the increased heat radiated by new, higher-energy rocket motors designed to boost payloads into orbit. AEDC measurements showed this to be true. Measurements of plume temperature during a Star 37XFP firing in 1985 inside Rocket Development Test Cell J-5 and calculations of heat radiation from the plume verified the Air Force Space Division’s analysis that critical GPS components such as the solar panels could receive as much as four times more heating than expected. As a result,



A full-scale GPS was tested in the Mark I Space Simulation Chamber at AEDC in 1977. The tests checked reliability of the satellite’s systems prior to its launch in 1978.



The GPS Block II underwent a four-month series of qualification tests to determine whether the satellite could withstand the extreme heat and cold in space.

engineers extended the satellite’s heat shield and altered the design of a portion of the solar panels to dissipate more heat.

Seven years later, AEDC test personnel completed life extension review and certification of two gaseous nitrogen storage vessels and one nitrogen distribution system. To minimize costs, the pressure vessel was transported to AEDC for recertification and was repaired using a qualified weld procedure, reinspected to verify repair of the defects, pressure tested, cleaned and painted in four weeks.

A year later, testing was conducted at the center to determine the high-temperature and ablation effects on the performance of GPS-frequency reentry antenna windows on spacecraft. There were three objectives to the test. The first was to evaluate effects of nonuniform ablation and temperature on the transmission and reflection abilities of antenna windows. The second was to obtain comparative window recession data for antenna window materials tested at severe reentry conditions; and the third was to obtain in-depth window temperature data to provide a basis for correlating the measured performance with internal window temperatures.

# ISS

## International Space Station

*Clearly visible with the naked eye in the night sky, the International Space Station is a working laboratory orbiting 240 miles above the Earth. It is the most complex scientific and technological endeavor ever undertaken, involving five space agencies representing 16 nations. As a research outpost, the station is a test bed for future technologies and a research laboratory for new, advanced industrial materials, communications technology, medical research and more. On-orbit assembly began in 1998 with the launch of Zarya. The ISS's solar panels exceed the wing span of a 777 wide-body jet and harness the sun's energy for electrical power to all station components and scientific experiments. Currently, station crews stay on orbit for six months at a time.*

### Characteristics

**Primary Function:** Orbiting Space Laboratory  
**Length:** 290 feet  
**Height:** 143 feet  
**Width:** 356 feet  
**Weight:** 1 million pounds  
**Living and Working Space:** More than 46,000 cubic feet  
**Average Orbit Altitude:** 220 miles, at an inclination of 51.6 degrees to the Equator  
**Accommodation:** Seven  
**First Launch:** November 20, 1998 (Zarya)



### Highlights of Development Testing at AEDC

#### • Tested hatch and cupola under vacuum conditions

The center began supporting the development of the International Space Station (ISS) in 1992 by testing a hatch for the station to help determine the hatch's ability to survive the extreme cold and hot temperatures of space.

The 200-pound, 53-inch-square hatch, which will close the passageway between compartments in the station, underwent the thermal/vacuum testing in AEDC's 12-foot vacuum chamber (12V). The actual point of interest was the latching mechanism on the hatch.

The test was necessary because the hatches are subjected to the space environment during their deployment. The test provided performance data on the hatch assembly when it was exposed to steady-state extreme temperatures and to cyclic thermal conditions.

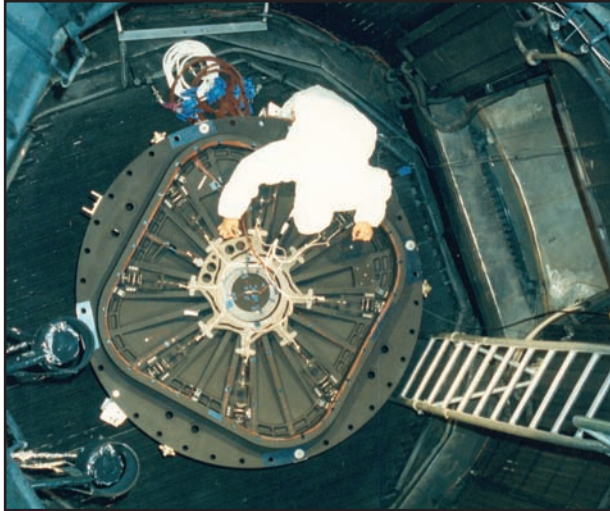
A solar simulator was used to heat the test article during warming portions of the thermal cycle. Cryogenic fluid in the chamber walls simulated the intense cold that is encountered in deep space.

The hatch assembly was subjected to three sets of thermal conditions during testing. The first was three "qualification" cycles representing expected worst-case temperatures, which range from -30 to 140 degrees Fahrenheit. The second was 120 orbital cycles representing expected on-orbit nominal conditions, 70 to 100 degrees Fahrenheit; and the third was three cold limit cycles to explore the lower operational limits of the hatch, -60 to 100 degrees Fahrenheit. The latch mechanism was activated – unlatched and latched – with a special test motor 130 times during the thermal cycles.

A year later, AEDC was again involved in testing an element of the ISS. A viewing cupola for the ISS was brought to AEDC, where it was covered in blankets, fitted throughout with heaters, and then placed in a space chamber, where it was subjected to temperatures as low as -300 degrees Fahrenheit. The cupola will be used by astronauts aboard the space station to provide 360-degree viewing. In space, the cupola's inside temperature will be controlled by heaters, multilayered insulation blankets located between the pressure wall and meteoroid debris shields, and thermal control coating on the shields. Outside, it will be exposed to the extreme environment of space.

Testing was necessary to find out what would happen to the

## International Space Station



**A Boeing technician calibrates limit switches on a hatch about to be tested in one of the center's environmental space chambers. The technician, 35 feet down in the chamber, is in white overalls to help keep the test section as clean as possible. The hatch is used on the International Space Station.**

windows when exposed to such contrasting pressure and temperatures. Boeing and NASA used the test information to verify the math modeling techniques previously gathered to quantify the heat conduction and thermal radiation properties of the cupola.

The test was performed in the 12-foot-diameter vacuum space chamber on a 400-pound, one-sixth section of the cupola. Chamber pressure was maintained below 10<sup>-5</sup> torr, which is equivalent to about 104 miles into space.

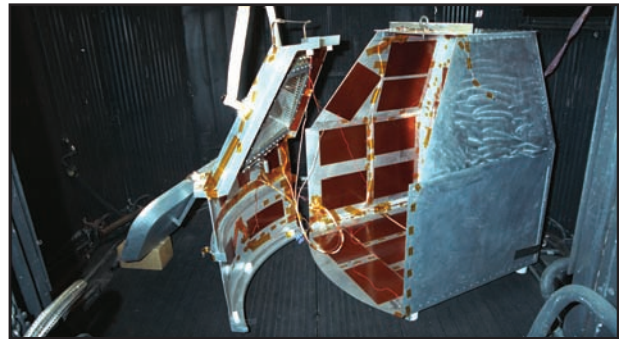
Two configurations of the model were tested – one with the window shutter closed, and one with it open. The cupola was heated internally to 40, 60 and 80 degrees Fahrenheit and held at each temperature until less than a half degree per hour change was achieved.

In 1995, Boeing returned to AEDC's 12V chamber, this time to determine the effects of exposing components of the ISS to the extreme temperatures of space. This latest space station component to be tested at the center was a full-size common berthing mechanism, the primary mechanical interface assembly linking the station modules together. The purpose of the testing was to gather thermal test data while exposing the component to simulated orbital conditions. The test information was needed to help validate the thermal model, define station keeping power requirements and verify material properties.

In such a test, inside the test chamber the mechanism is exposed to space-like conditions. Vacuum pumps evacuate the air while the chamber walls are cooled by liquid nitrogen and an array of xenon arc lamps produce a collimated beam of light spectrally equivalent to the sun. The chamber support structure allows the test article to rotate from horizontal through vertical during a cycle. More



**An AEDC rigger helps lower an ISS component – a common berthing mechanism – into the 12V chamber in 1995.**



**A model of a cupola for the ISS is ready for testing inside the space chamber. The open panel reveals heaters and instrumentation applied to the model.**

than 700 thermocouples are used to provide the necessary thermal data. Two test article configurations were tested – one an active common berthing mechanism and the other, a passive one. These are the two 6-foot-diameter rings that seal the joint between station modules upon mating. The first ring, called active, houses the powered bolts and actuators that drive the two halves together. The second, or passive ring, provides a seal between the modules when the two halves are mated.

Both configurations include a berthing plate, hatch assembly, multi-layer insulation blankets and component hardware associated with each type. The test matrix included 34 different thermal cycle configurations and took roughly 68 days to finish.

# Cassini-Huygens

*The Huygens Probe was designed by the European Space Agency to perform an in-depth study of the clouds, atmosphere and surface of Saturn's largest moon – Titan. Traveling onboard the Cassini orbiter throughout the seven-year journey to Saturn, the Huygens probe separated from the Cassini orbiter in December 2004 and began a 20-day coast phase toward Titan. In January 2005, just four hours before reaching the atmosphere of Titan, timers “woke up” the Huygens probe. The Huygens probe was the first spacecraft to land on a moon in the outer Solar System.*

## Characteristics

**Primary Function:** Fly-by, orbiter and lander

**Contractor:** NASA/European Space Agency

**Electrical Power Source:** Three radio-isotope thermo-electric generators (RTG) 885 W

**Optical Remote Sensing**

**Instruments:** Will determine temperatures, chemical composition, structure, and chemistry of Saturn, its rings, moons, and their atmospheres; will measure the mass and internal structure of Saturn and its moons; will photograph Saturn, its rings and moons, in visible, near-infrared, and ultraviolet wavelengths.

**Radar:** Will map Titan and measure heights of surface features

**Width:** 13.1 feet

**Height:** 22 feet

**Maximum Takeoff Weight:** 5,842 pounds

**Date Deployed:** Oct. 15, 1997

**Inventory:** 1



## Highlights of Development Testing at AEDC

- Tested Huygens probe parachute drag and deployment
- Tested upgraded LR-91 rocket engine

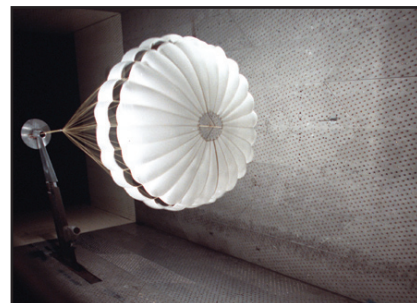
When NASA's Cassini spacecraft lifted off for Saturn in May 1996 so did the results of work performed at AEDC.

The Cassini was the first vehicle to visit the planet since the Pioneer and Voyager missions in the 1980s.

During a four-year test support program, AEDC played a critical role in this joint NASA and European Space Agency (ESA) mission. Center employees tested the launch vehicle's second-stage LR-91 propulsion system vehicle and the probe's parachute deployment system.

In 1993, PWT facility employees successfully conducted parachute deployment and drag performance tests on a 3/16-scale, 22-inch-diameter model of the ESA Huygens probe in the 16-foot transonic wind tunnel (16T). AEDC's tunnel was chosen because it could test a larger scale model and better simulate flight conditions than any other available test facility. During the tests to simulate Titan's atmosphere, air pressures equivalent to those the probe would experience in space at an altitude of 82,000 feet above sea level were generated. The probe model returned to AEDC in 1994 and underwent additional, similar parachute deployment testing.

In 1995, the U.S. Air Force Space and Missile Systems Center chose Rocket Development Test Cell J-4 to evaluate structural integrity of new nozzle engine skirts used on the Aerojet LR-91 engine, which serves as the Titan IV's second-stage propulsion unit. To support NASA test requirements, AEDC accelerated J-4 reactivation and added storable liquid propellant testing capabilities. On June 1, 1996, employees at AEDC successfully test-fired the engine, validating the new nozzle extension skirt's performance.



The ESA Huygens was tested in 16T. The model of the probe was fitted with scaled main and pilot parachutes, which were opened at speeds ranging from 350 to 1,000 mph.

# EELV

## Evolved Expendable Launch Vehicle

The Evolved Expendable Launch Vehicle (EELV) program is designed to improve the nation's access to space by making space launch vehicles more affordable and reliable. The program replaced the legacy fleet of launch systems with two families of launch vehicles, each using common components and common infrastructure. The vehicles are the Boeing Delta IV and Lockheed Martin Atlas V. EELV's operability improvements over legacy systems include a standard payload interface, standardized launch pads and increased off-pad processing. As the Air Force's space-lift modernization program, EELV was designed to reduce launch costs by at least 25 percent over legacy Atlas, Delta and Titan space launch systems.

### Characteristics

#### Delta IV

**Primary Function:** Space launch

**Contractor:** Boeing

**Thrust:** 663,000 pounds

**Diameter:** 16.4 feet

**Height:** 206-253.2 feet

#### Atlas V

**Primary Function:** Space launch

**Contractor:** Lockheed Martin

**Thrust:** 663,000 pounds

**Diameter:** 12.5 feet

**Height:** 191.2 feet



### Highlights of Development Testing at AEDC

- Payload fairings separation testing in Mark I
- Motor tested in J-4 to ensure successful launch

The Evolved Expendable Launch Vehicle (EELV) program is a U.S. government, primarily DoD-sponsored, effort to develop at least one family of space launch vehicles that would meet the long term needs of the military and fulfill commercial and government need for cost-efficient and reliable access to earth orbit.

The Air Force assembled its initial blueprint for the EELV in 1994, following many years of government-funded studies into an improved system and architecture, which was intended to replace all if not most existing "legacy" spacelifters. The architecture called for the spacelifter to be based on standardized fairings, liquid-core vehicles, upper stages and solid rockets. The standard payload interface was also proposed as another way to save money and improve efficiency.

On Nov. 20, 2002, the Boeing Delta IV made its first successful flight from Cape Canaveral, Florida.

AEDC's Rocket Development Test Cell J-4 was instrumental in the successful launch through simulated altitude tests on the Pratt & Whitney (P&W) RL10B-2 upper-stage engine, the same type used in the Delta IV.

In 1997, 1998 and 2001, AEDC crews tested the 25,000-pound-thrust engine at simulated altitudes up to 100,000 feet in the J-4 test cell. The RL10B-2 utilizes the largest area ratio nozzle employed in spacelift operations.

The J-4 test cell provides a unique capability to test these large-area nozzles by providing a "soft" shutdown at the end of engine burn. The soft shutdown prevents back pressures from damaging the nozzle.

In December 1997, AEDC's Mark I Space Simulation Chamber supported the EELV program to see what actually happens to the protective payload covering during separation. Using a linear explosive assembly, AEDC and Boeing completed separation of a full-scale segmented fairing from a Delta III launch vehicle. Engineers conducted qualification testing on the new Boeing Delta III composite payload fairing (PLF) in the Mark I Environmental Space Chamber.

Manufactured by McDonnell Douglas, Inc., the Delta III PLF is a 13-foot, 4-inch-diameter composite fairing standing 35 feet high. It consists





**Lockheed Martin Astronautic designers and AEDC engineers conducted aerodynamic tests on the Atlas V in wind tunnel 16T to help Lockheed Martin determine detailed local acoustic and vibration environments as well as whole vehicle buffet load environments.**

of two bisector segments, each weighing approximately 1,600 pounds, that separate from the launch vehicle after leaving the Earth's atmosphere.

The purpose of the PLF is to protect payloads on the Delta III from aerodynamic and thermal environments during launch. The Delta III initially was used to launch commercial satellites and later became part of the EELV program.

During the test, the PLF separated at a simulated altitude of 255,000 feet and reached a maximum speed of 18 feet per second. The separation consisted of two explosive events – the fracture of two bolts at the base of the PLF, followed by the detonation of a linear explosive assembly that simultaneously splits the PLF vertically in half and propels it away from the payload. Following a 6-foot free-flight condition, a unique Boeing-developed catch system slowed and stopped the segments without damaging them.

The primary objectives of this 1997 test were to demonstrate successful separation, measure shock induced by the explosive devices to the payload and to critical vehicle systems, and record the post-separation motion of the bisector segments. The information obtained during the test, combined with analytical modeling, qualified the payload fairing system for flight.

In March 1999, AEDC was once again supporting the EELV program. This time, the center was testing the P&W

RL10B-2 nozzle in the J-4 test cell to ensure the success of an upcoming Delta III launch.

The RL10B-2 is the upper-stage propulsion system used for the Delta III and Delta IV launch vehicles and the EELV.

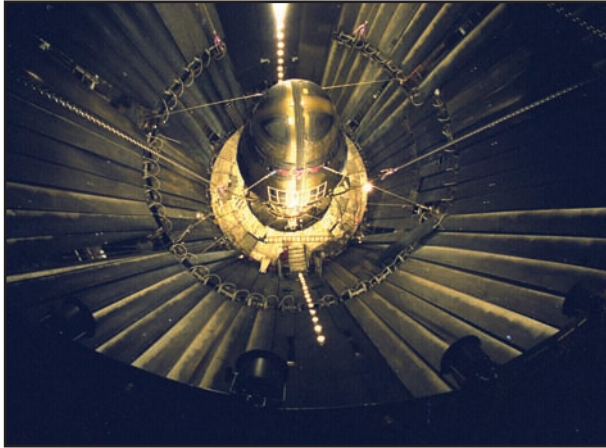
Using a large-area ratio exhaust nozzle, the engine provides second-stage, high-performance thrust that enables the rocket to place increased payloads into Earth's orbit.

The test program began in December 1998 with only a single test planned on the Nozzle Extension Deployment System (NEDS). Test engineers in J-4 conducted that test Dec. 23 despite bitter cold and icing conditions.

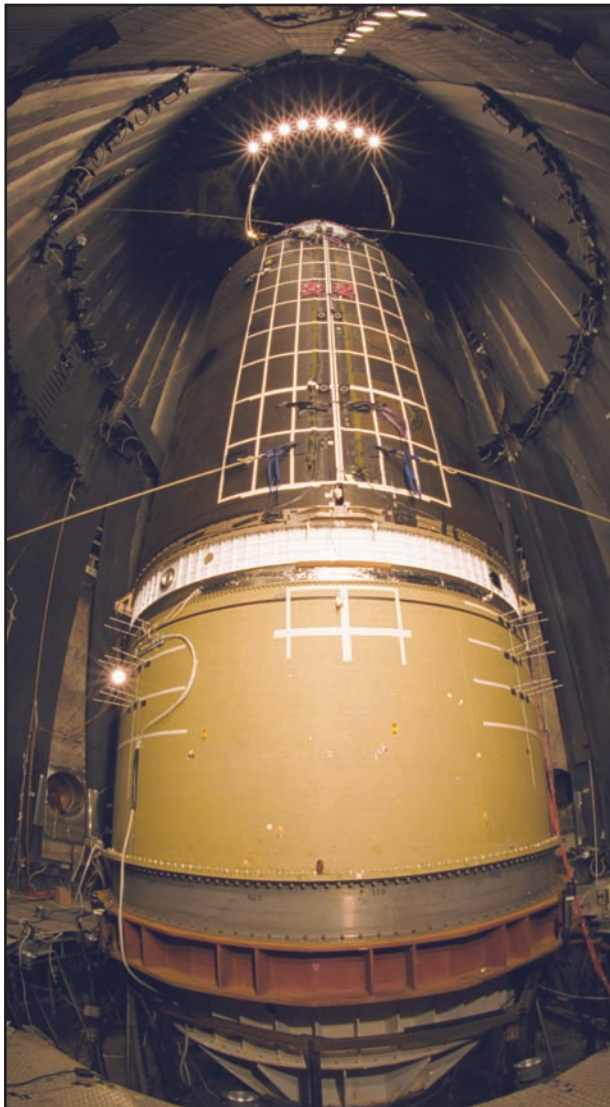
Data from that test revealed an anomaly in the deployment phase. The icy conditions made it challenging to conduct the test, but getting the test off that day was critical since it showed a problem that needed to be corrected. Boeing officials took advantage of that window of opportunity to develop solutions and conduct further evaluations. As a result, they added two tests to the program.

In preparation for the additional tests, AEDC employees installed stainless steel shrouds designed to protect the NEDS belt against thermal effects of the liquid hydrogen chilldown that occurs prior to nozzle deployment. They also built two systems to simulate conditions the nozzle would experience during launch. The first system consisted

## Evolved Expandable Launch Vehicle



This 35-foot high Delta III payload fairing underwent testing in Mark I Space Environmental Chamber to ensure it would operate in space. The fairing's two bisector segments separated at a simulated altitude of 255,000 feet. Below, looking up from the bottom of the Mark I test chamber.

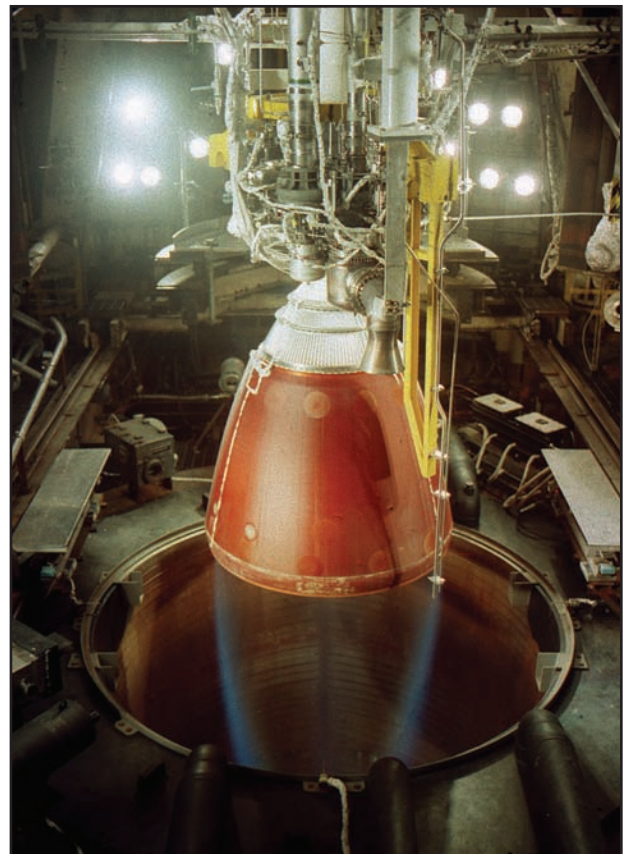


of an AEDC-designed interstage that connected the launch vehicle's Stages I and II and simulated the environment around the engine. This created near-real-space temperature conditions caused by engine chill-down fuel flows. The second system simulated zero-gravity conditions using a Boeing-designed pulley system with weights exactly matching the weight of the nozzle during deployment.

During the tests, fuel-flow chilldown prompted automatic sequencers to open the bottom of the interstage opening to simulate second-stage separation. At that point, nozzle deployment commands initiated automatically, allowing evaluation of the deployment sequence to determine if the nozzle extension latched within a specified time before ignition.

Data showed the nozzle successfully deployed and latched into place within specifications.

In October 2001, AEDC completed qualification of the nozzle design with four successful runs and saved the Delta IV test team more than \$100,000 in test costs. The nozzle is critical to providing the necessary performance for the heavy-payload launch vehicle.



A Titan IV second-stage engine was tested in Test Cell J-4 in 1996. The test set a facility record with the 300-second firing.

# Chandra

*The Chandra X-Ray Observatory combines its mirrors with four science instruments to capture and probe the X-rays from astronomical sources. The incoming X-rays are focused by the mirrors to a spot about half as wide as a human hair on the focal plane about 30 feet away. The focal plane science instruments provide information about the incoming X-rays: their number, position, energy and time of arrival.*

*The Chandra telescope system consists of four pairs of mirrors and their support structure. Two additional spectrometers provide detailed information about the X-ray energy.*

*Chandra has two different sets of thrusters: one for propulsion and the other for momentum unloading. The propulsion thrusters were used immediately after launch to help propel Chandra into its final orbit, which is elliptical and very high in altitude. The momentum-unloading thrusters are periodically used to apply torques to Chandra and, thereby, lower the accumulated momentum in its reaction wheels, which are used to control Chandra's attitude.*



## Highlights of Development Testing at AEDC

- Validated operations and survivability of Chandra's solar panels
- Certified the instrument cables were free of contaminants that might hinder the satellite's optical systems

In 1999, the Chandra Advanced X-ray Astrophysics Facility-Imaging Satellite, a space-based observatory with the ability to collect X-ray images from space, was carried into space aboard the space shuttle *Columbia*.

Many of Chandra's components were tested at AEDC. In 1996, AEDC tested the Chandra's solar array panels and instrument cables in four of its space environmental chambers. At that time, the project was known as the Advanced X-ray Astrophysics Facility-Imaging (AXAF-I) satellite.

AEDC's role was to validate the operations and survivability of the solar panels that power the observatory since the panels play a key role in the long-term survivability of the observatory, providing power to all on-board systems.

AEDC conducted 152 thermal cycles, representing 10 years of orbital flight, in the 3-by-5 chamber to validate the materials in the Proto-Flight Solar Array Panel. During the cycles, the panels were subjected to alternating extreme hot – 161 degrees Fahrenheit – and cold – -330 degrees Fahrenheit – conditions similar to those the system would experience in an elliptical orbit.

AEDC engineers validated the workmanship of the Chandra's 7-foot, 2-inch-thick solar array panel and associated hardware under vacuum and harsh temperature conditions – as low as -400 degrees Fahrenheit – in the 10V Chamber. The one-week test consisted of 11.5 thermal cycles, representing a little more than six months in orbit.

Finally, the instrument cables were pre-baked in the 4-by-10 thermal vacuum chamber at 200 degrees Fahrenheit. These tests certified that the cables were free from the typical cable contaminants that hinder the satellite's optical systems.

The cables were then placed in the 7-by-8 chamber and heated to 160 degrees Fahrenheit until they were contaminant-free. Following the tests, the cables were double-bagged in anti-static bags in the chamber's Class 1,000 clean room and returned to NASA.

## Characteristics

**Size:** 45.3 feet by 64 feet

**Weight:** 10,160 pounds

**On-orbit life:** More than five years

**Electrical Power:** Two 3-panel, silicon solar arrays provide 2,350 watts of power (end of life)

**Antenna:** Two low-gain, conical log spiral antennas provide spherical coverage

**Frequencies:** Transmit 2,250 megahertz; Receive 2,071.8 megahertz

**Command Link:** Two kilobits per/sec

**Data Recording:** Solid-state recorder; 1.8 gigabits (16.8 hours) of recording capacity

# GOES-M

## Weather Satellite

*The GOES-M provides all of the world's weather satellite images, including Doppler radar, shown on TV weather programs and Internet weather sites. These satellite images assist with the observation and prediction of developing thunderstorms, tornados, flash floods and snowstorms. GOES-M can also monitor dust storms, volcanic eruptions and the progression of forest fires. Built and launched under NASA management for the National Oceanic and Atmospheric Administration (NOAA), the 3,400-pound GOES-M satellite is the fifth of five advanced weather satellites operated by NOAA and was designed to help improve forecasting of Earth's weather and space weather. GOES-M is the first to have a sophisticated operational instrument for detecting solar storms.*

### Characteristics

**Launch:** July 22, 2001, from Kennedy Space Center  
**Orbit:** Altitude: 36,000 km  
**Inclination:** 98 degrees; Period: 45 minutes; Geo-Synchronous  
**Weight:** 4,600 kg  
**Size:** 27 meters  
**Power:** 1,050 watts  
**Design Life:** Five years  
**Instruments:** Solar X-ray Imager, Space Environment Monitor, Sounder, Search and Rescue



### Highlights of Development Testing at AEDC

- **Mandatory validation testing of the Geostationary Operational Environmental Satellite-M (GOES-M) at space conditions similar to its orbital path**
- **Space simulation testing of the GOES-M that helped the satellite's launch stay on schedule and confirmed its eligibility to withstand actual space conditions in orbit**

Loral Space and Communication and AEDC signed a 10-year contract in March 1999 to test the company's satellites at the center.

A little more than a year later, in July 2000, AEDC tested the first Geostationary Operational Environmental Satellite-M (GOES-M) in its Mark I Space Simulation Chamber as a part of that contract.

Mark I employees tested the satellite at space conditions similar to its orbital path. During the test, the Mark I chamber was pumped to a vacuum pressure of  $10^{-7}$  torr (less than one-billionth of normal air pressure), and the walls were cooled to -321 degrees Fahrenheit. Using special heaters to simulate solar effects, they tested the GOES-M at winter, summer, spring and fall temperatures in space. The test's purpose was to validate how the satellite would operate in simulated orbital environment, including cryogenic and solar temperatures under vacuum conditions. The GOES-M was designed to help meteorologists worldwide track and predict the weather.

At a 22,750-mile orbit, the GOES-M provides all of the world's weather satellite images, including Doppler radar, which is shown on television weather programs and Internet weather sites. These satellite images assist with the observation and prediction of developing thunderstorms, tornadoes, flash floods and even snowstorms. GOES-M has also helped to monitor dust storms, volcanic eruptions and the progression of forest fires.

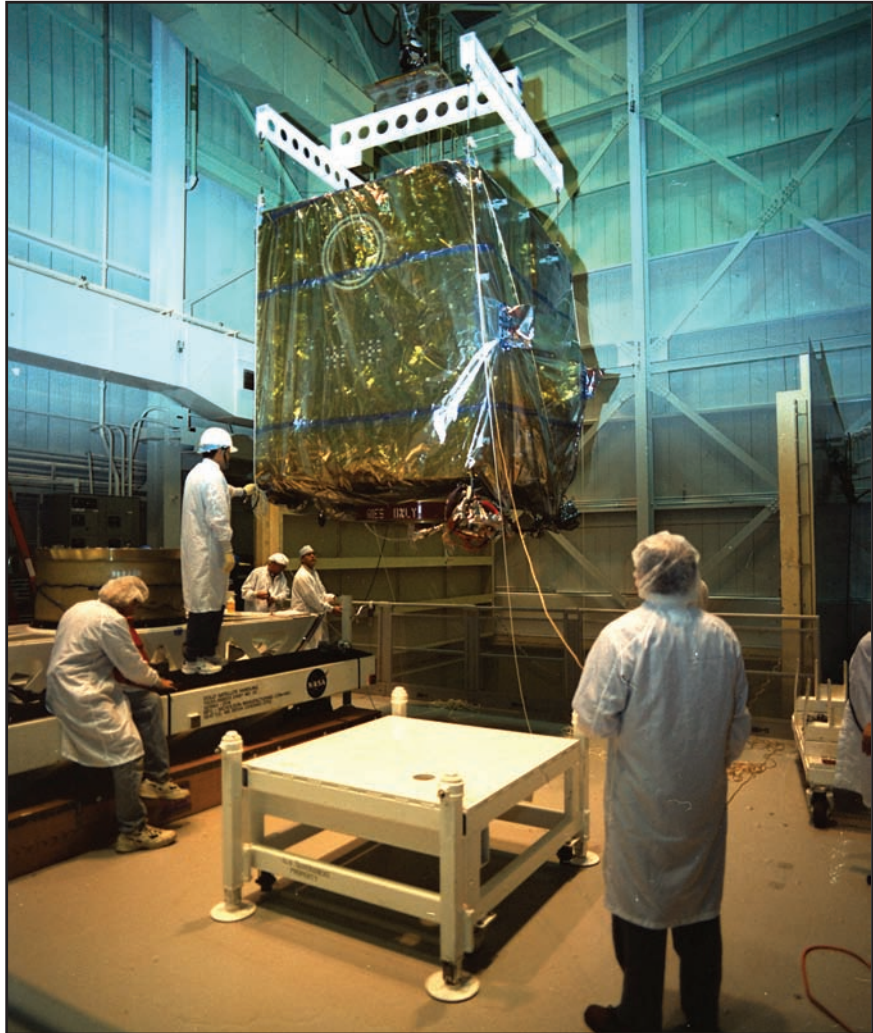
Using various sensors, a space environmental monitor and a Solar X-ray Imager telescope, the satellite monitors three main

components of space weather – X-rays, energetic particles and magnetic fields, including the sun’s solar flares activities. The system also helps scientists study the effects of solar activity on Earth’s telecommunication systems. AEDC tests confirmed satellite operation under simulated space conditions before it was placed in orbit.

In the fall of that same year, AEDC set a new test duration record on the GOES-M when the thermal vacuum test, conducted to validate the satellite in simulated orbital environment, including cryogenic and solar temperatures under vacuum conditions, lasted 45 days, 22 hours and 10 minutes.

The previous record of 44 days, 23 hours and 14 minutes was set in Mark I during a Global Positioning Satellite (GPS) Block II test in 1985. The 3,400-pound GOES-M also contains a Solar X-Ray Imager telescope that will monitor the sun’s solar flare activities.

On July 23, 2001, after performance validation tests at AEDC, the GOES-M was successfully launched at the Kennedy Space Center at Cape Canaveral Air Force Station in Florida.



**The GOES-M Weather Satellite is hoisted into the clean room in the Mark I Space Chamber.**



**The GOES-M Weather Satellite was delivered on a C-5C.**



**The GOES-M handling dolly arrives at Mark I.**

# X-43

## Hyper-X



The X-43, part of NASA's Hyper-X program, is an unmanned experimental hypersonic aircraft design with multiple scale variations meant to test different aspects of high supersonic flight.

A winged booster rocket with the X-43 itself at the tip, called a "stack," was launched from a carrier plane. After the booster rocket – a modified first stage Pegasus rocket – brings the stack to the target speed and altitude, it is discarded, and the X-43 flies free using its own engine, a scramjet.

The initial version, the X-43A, was designed to operate at speeds greater than Mach 7, about 5,000 mph at altitudes of 100,000 feet or more.

The third, slightly different version, successfully flew at Mach 10.

On June 20, 2005, NASA was recognized for setting the speed record for a jet-powered aircraft by Guinness World Records.

### Characteristics

**Primary Function:** Unmanned experimental hypersonic aircraft

**Contractor:** Boeing

**Power Plant:** Alliant Techsystem Orion 50S solid rocket motor

**Thrust:** 109,000 pounds

**Wingspan:** 22 feet

**Length:** 49 feet

**Weight:** 37,300 pounds

**Diameter:** 50 inches

**Performance:** Separation conditions between Mach 7 and 10 at 95,000 to 110,000 feet

#### X-43A

**Length:** 12 feet

**Wingspan:** 5 feet

**Weight:** Approximately 3,000 pounds

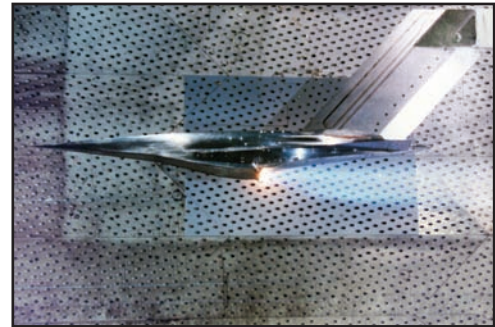
**Propulsion:** Dual-mode ramjet/scramjet

### Highlights of Development Testing at AEDC

- Arc heater tests of nose/leading edge materials
- Aerodynamic tests

In 2000, NASA Langley Research Center used AEDC's H-2 arc heater to evaluate potential nose leading-edge materials before flight testing three hypersonic air-breathing vehicles during the following two years.

AEDC was the only facility that could provide the pressure needed to evaluate the materials. Simulating flight conditions in the AEDC H-2 arc facility convinced the customer that if the materials survived the AEDC tests, they would survive the flight.



A model of the X-43 Hyper-X was tested in an AEDC wind tunnel.

The first two Hyper-X (X-43) vehicles flew at Mach 7 conditions using

a silicon carbide-coated carbon/carbon for the horizontal control surfaces and nose leading edge. Those materials are designed to withstand maximum temperatures below 3,000 degrees Fahrenheit.

The third, slightly different, vehicle flew at Mach 10 and was exposed to a more severe thermal environment that exceeded the single-use temperature of Mach 7 leading-edge materials.

High-temperature coatings were evaluated at AEDC in an effort to utilize passive carbon/carbon material leading edges for the Mach 10 vehicle. Ensuring that these materials survive the flight was critical because leading-edge recession may contaminate the air-breathing engine as well as effect vehicle control.

During the tests, the H-2 team evaluated 24 wedge-shaped leading-edge samples at Mach 10 conditions of 2,200 British Thermal Unit (BTU) per pound and stagnation pressures of 1.2 atmospheres pressure. The results were good, as more than one sample survived multiple tests.

# X-37

## Advanced Technology Vehicle



*The Boeing X-37 advanced technology flight demonstrator was intended to test future launch technologies while in orbit and during atmospheric reentry.*

*More recently, the Air Force decided to use the X-37 as a reusable robotic spacecraft – a 120-percent scaled derivative of the X-40A. An autonomous, self-flying vehicle, the X-37 is about 27 feet long and weighs approximately 7,000 pounds. Capable of being ferried into orbit on an expendable launch vehicle, the X-37 will operate at speeds up to 25 times the speed of sound. The X-37 flew its first flight as a drop test on April 7, 2006, at Edwards Air Force Base.*

### Characteristics

**Primary Function:** Advanced technology flight demonstrator

**Contractor:** Boeing

**Power Plant:** Initially none, follow up vehicle may have one Rocketdyne AR2-3

**Thrust:** 7,100 pounds

**Wingspan:** 14 feet, 4 inches

**Length:** 25 feet, 7 inches

**Maximum Speed:** Potentially Mach 25

**Maximum Takeoff Weight:** 12,000 pounds

**Crew:** Unmanned

**Armament:** None

**First Flight:** April 7, 2006

### Highlights of Development Testing at AEDC

- **Aerodynamic loads testing on scale models of the X-37 to gather information for a final verification database to be used for designing the flight control system for the vehicle**
- **Studies of aerodynamic jet interaction effects resulting from small reactor control system jets on the aft section of the X-37**

AEDC conducted aerodynamic loads testing on scale models of the Boeing X-37 Advanced Technology Vehicle to gather information for a final verification database to be used for designing the flight control system for the vehicle. A team at the center also studied aerodynamic jet interaction effects resulting from small reactor control system jets on the aft section of the X-37.

In 2001, AEDC engineers collected data during two series of wind tunnel tests that contributed to the final design and support of flight tests.

Conducted for Phase II of Boeing's X-37 Wind Tunnel Test Program, the tests occurred in the center's von Kármán Gas Dynamics Facility (VKF) wind tunnels.

In this series of tests, a 6-percent scale, final configuration model of the X-37 was tested in Tunnel A to examine the vehicle's aerodynamics at speeds ranging from Mach 1.5 to 5.0. This phase of the wind tunnel test program evaluated the frozen vehicle lines or exterior shape. Data from these tests were used to generate the final verification database from which the flight controls system will be designed, leading to development of its avionics and software that will fly the vehicle during the autonomous (self-flying) entry phase.

During this second round of wind tunnel tests, engineers acquired data in Tunnels A, B and C to determine aerodynamic jet interaction effects from plumes of small reaction control system jets located near the aft end of a 6-percent scale vehicle model.

Many vehicles use jets on different parts of the structure to control their attitudes, instead of flaps, rudders or similar devices. This test entry

## X-37 Advanced Technology Vehicle

gave AEDC the opportunity to conduct testing for vehicles with jet interaction.

Derived from the Air Force's X-40A, a Boeing prototype Space Maneuver Vehicle, the X-37 is an offspring of the NASA Pathfinder Program, which focuses on reducing the cost of space access through advanced space technologies.

In December 1998, NASA entered into a four-year cooperative agreement with the Boeing Company to develop the Future-X Pathfinder flight demonstrator vehicle, now known as the X-37. The X-40 and X-37 contain some similarities but differ slightly in configuration. An autonomous (self-flying) vehicle, the X-37 is about 27 feet long and weighs approximately 7,000 pounds. Powered by an AR-2/3 engine, which uses JP-10 jet fuel and hydrogen peroxide as propellants, the vehicle has a 7,000-pound thrust capacity and currently contains no ascent phase in its program.

During another series in the test program, AEDC's X-37 Reaction Control System (RCS) Core Test Team developed and implemented a new RCS data acquisition and data reduction methodology, which resulted in improved data accuracy and significant cost avoidance.

The test team proposed a new data acquisition method of taking continuous data while sweeping the RCS jet mass flow, cutting the tunnel time by two-thirds and making the technique affordable for the customer.

The team designed and AEDC fabricated a new mass-flow balance using improved techniques developed by the Balance Technology project to accommodate the customer's request for a more accurate balance. The balance supports a model under test in the wind tunnel and measures airflow-caused forces and moments impacting the model.

The accuracy of the measurements was further enhanced with a new high-gain data acquisition and calculation method.

These improvements — the mass-flow sweep jet interaction, the improved balance and the high-gain data reduction — proved useful for J-1 tests to improve data productivity and accuracy.

The X-37 was originally designed to be carried into orbit in the space shuttle cargo bay but underwent redesign for launch on a Delta IV or comparable rocket, when it was determined a shuttle flight would be uneconomical.

The vehicle currently operating is an atmospheric drop test vehicle. It has no propulsion system, and where the payload bay doors of an operational vehicle would be, it has a fixed strongback structure instead to allow it to



**A 6-percent scale model of NASA's X-37 underwent testing in tunnels A, B and C to establish how redesigns to the demonstrator spacecraft's control jet nozzles and body flap effected its aerodynamics during reentry into and through the Earth's atmosphere.**



**A wind tunnel test in VKF used a 6-percent scale model of Boeing's X-37 to investigate the aerodynamic forces and moments of the vehicle and aerodynamic jet interaction effects from plumes of small reaction control system jets on the model.**

be mated with a mothership. Also, most of the thermal protection tiles are fake, made of inexpensive foam, rather than ceramic. (Certain tiles in key areas are genuine, as are the Thermal Protection System [TPS] blankets in areas where heating is not severe enough to require tiles.)

On June 21, 2005, the X-37 completed a "captive-carry" flight underneath the White Knight at Mojave Spaceport, Mojave, California.

The X-37 flew its first flight as a drop test on April 7, 2006.



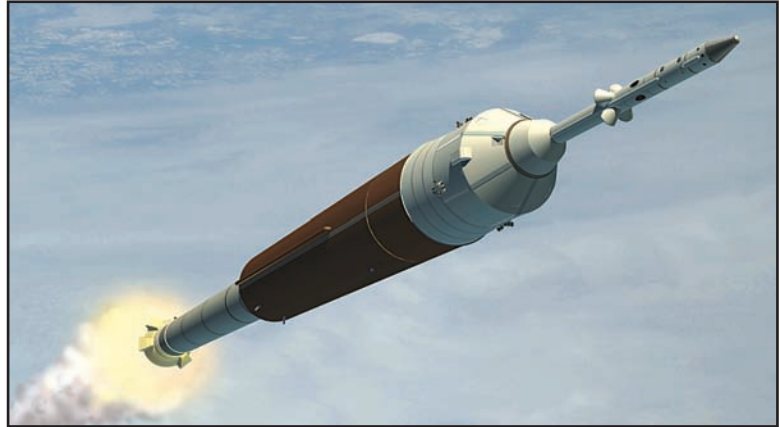
# CEV

## Crew Exploration Vehicle

*The Crew Exploration Vehicle (CEV) is America's new spacecraft for human space exploration. It will be able to ferry crews of three astronauts – plus additional cargo – to and from the International Space Station but has the capability to carry as many as six crew members. A Crew Launch Vehicle (CLV) consisting of a solid rocket booster and a space shuttle main-engine-driven upper stage will carry the spacecraft into orbit. Research indicates that each spacecraft can be flown up to 10 flights. Multiple spacecraft will be built, part or all of which may be reusable. The flight schedule will determine how many vehicles need to be built. NASA is working to make the new spacecraft operational by 2014, in order to minimize any gap in human space flight due to the retirement of the space shuttle.*

### Characteristics

**Primary Function:** Manned spacecraft  
**Contractor:** Lockheed Martin  
**Date Deployed:** Scheduled IOC 2014  
**Inventory:** 0

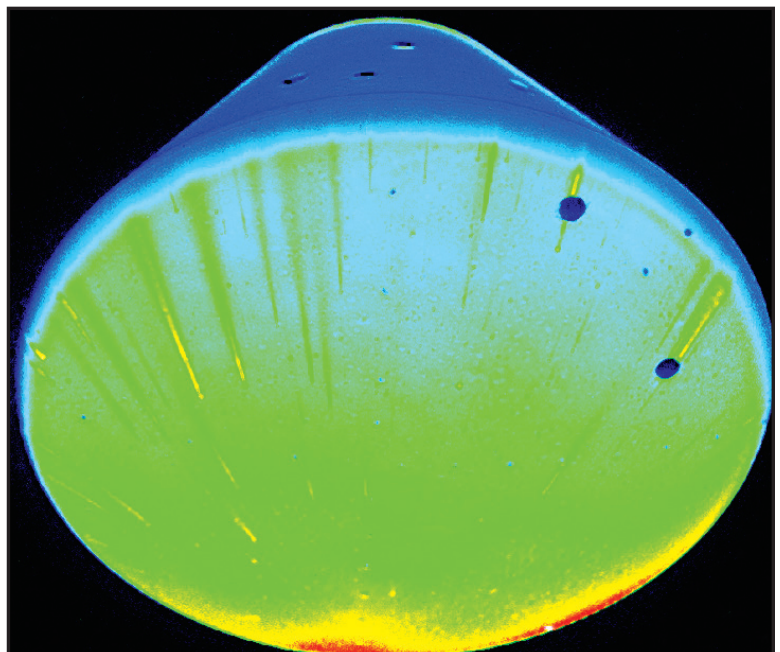


### Highlights of Development Testing at AEDC

- **Aerothermal testing at Tunnel 9**
- **Arc Heater testing of heat shield ablative materials at AEDC**

In 2006, NASA selected Lockheed Martin Corp., as the prime contractor to design, develop, build, test and evaluate the Orion Crew Exploration Vehicle (CEV), the next generation manned spacecraft. The CEV will be the replacement vehicle for the current space shuttle fleet.

The Orion program will provide a state-of-the-art human space flight system capable of safely transferring astronauts to and from the International Space Station (ISS), the moon, Mars and other destinations beyond low Earth orbit. Orion will be able to transport four crew members for lunar missions and support crew transfers for Mars missions.



Temperature sensitive paint fluoresces on the surface of the Crew Exploration Vehicle's heat shield during a Mach 10 run at Tunnel 9.



**A University of Maryland graduate student and an ATA engineer examine the illuminated TSP coating on the NASA CEV model prior to a run at Tunnel 9.**

In 2006, AEDC's Tunnel 9 made use of conventional and advanced measurement techniques during the aerothermal testing of NASA's scale model of the new Orion crew exploration vehicle command module.

The primary objective of the Orion testing at Tunnel 9 was to obtain heating data over the model's surface covering the full operational range of the facility at Mach 8 and 10 freestream conditions.

Unlike the development of the Apollo capsule, where the database was populated entirely using experimental data, the Orion database is being developed using advanced Computational Fluid Dynamics (CFD) modeling techniques. The experimental data will be used to validate the CFD models for NASA's Orion database development.

Tunnel 9's unique high Mach number and high-pressure capabilities allowed NASA to obtain data on the vehicle that they were not able to obtain in any other facility.

Another team at Tunnel 9 supported the CEV test by pushing the use of Temperature Sensitive Paint (TSP) to its limits during the project's final phase. Their goal was to further develop and demonstrate TSP's effectiveness and viability to collect test data in Tunnel 9's unique high-temperature and high-pressure hypersonic environment. TSP, which is similar to Pressure Sensitive Paint (PSP), is a system that includes a special paint, an ultraviolet illumination source and a sensitive charge-coupled device (CCD) camera to obtain surface-temperature data. The paint is applied to the model in two layers – a white

undercoat and the TSP layer. The white undercoat provides a uniform reflective surface for the TSP. The illumination source excites the TSP layer, which fluoresces a bright red color with its intensity inversely proportional to the surface temperature on the model.

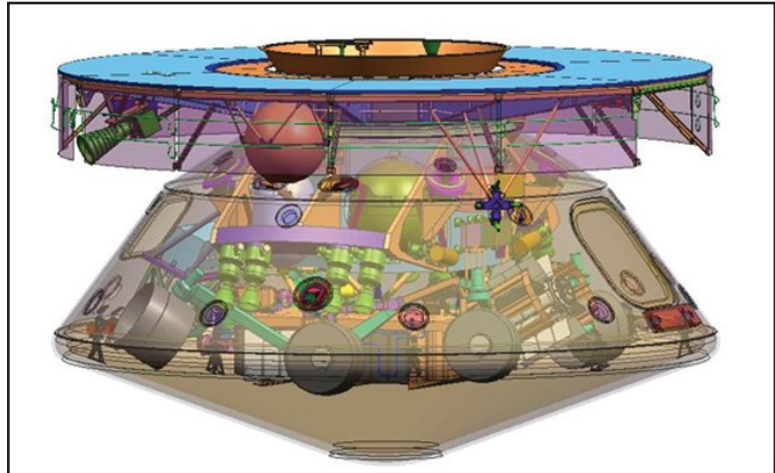
The traditional way of collecting heat-transfer data is by use of discrete sensors, placing them at various locations on the test article and collecting data at a single point in certain areas. The problem with this method is that it's difficult to instrument areas like the leading edges of models, fins and controls surfaces. Frequently the engineers do not have prior knowledge of where gages should be placed. Furthermore, the discrete sensors are expensive and require a lot of work to install and wire electrically, sometimes taking over a month to prepare if a model is heavily instrumented. TSP allows use of what is described as a global mapping technique to get the desired parameter (heat transfer, in this case) from the entire surface of the test article. It's effectively like acquiring data from tens of thousands of thermocouples.

The team at Tunnel 9 had to deal with some technical challenges not experienced at other facilities working with TSP and PSP. Tunnel 9's combination of relatively short run times and high heating rates presents challenges that are unique in the world of TSP/PSP. High-quality, high-output, stable illumination fields are needed to combine with high-end scientific-grade CCD cameras to take images at frame rates fast enough to calculate heat transfer.

# Mars Science Laboratory

*Scheduled for launch in 2011, Mars Science Laboratory (MSL) is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of Mars. MSL will access whether Mars ever was, or is still today, an environment able to support microbial life.*

*Arriving at Mars in 2012, MSL will serve as the beginning to the next decade of Mars exploration. It represents a huge step in Mars surface science and exploration capability because it will demonstrate the ability to land a very large, heavy rover on the surface of Mars; demonstrate the ability to land more precisely in a 12.4 mile landing circle; and demonstrate long-range mobility on the surface of Mars for the collection of more diverse samples and studies.*



## Highlights of Development Testing at AEDC

- **Atmospheric Entry tests at Tunnel 9**
- **Parachute deployment test at NFAC**

The Mars Science Laboratory (MSL) is being developed by NASA as part of the Mars Exploration Program. A sophisticated, mobile laboratory, the MSL will use precision landing to analyze dozens of samples scooped from the soil and cored from rocks as it explores with greater range than previous Mars rovers. Carrying the most advanced payload of scientific gear ever used on Mars' surface, the mission is to investigate the past or present potential of Mars to support microbial life.

In 2006, a team at AEDC's Tunnel 9 successfully completed atmospheric entry testing of the aeroshell configuration for the MSL, scheduled to launch in the fall of 2011 for a seven-month journey to Mars.

NASA has selected an Atlas V rocket for the mission. A fairing will protect the spacecraft during the ascent through the Earth's atmosphere. It also will support a large aeroshell – the protective heat shield and back shell that protects the rover during entry through the Martian atmosphere – as well as the rover mass.

The objective of this particular test program was looking at the aerodynamic characteristics of this delivery vehicle, the aeroshell, which will house the rover and instrumentation suite. Since the entry into Mars' atmosphere is going to be a precision trajectory, a high degree of accuracy will be needed in characterizing the flowfield around the capsule as it enters the Martian atmosphere. The flowfield around the vehicle, whether laminar or turbulent, directly affects how the vehicle is guided to its landing site. The team wanted to understand the flowfield developing on the capsule as it enters the atmosphere.

Tunnel 9 used nitrogen as a test fluid when simulating the vehicle trajectory into the Martian atmosphere, which is composed primarily of carbon dioxide and is considerably less dense than Earth's atmosphere.

The data set from Tunnel 9 was used to validate the NASA Computational Fluid Dynamics (CFD) model being used to evaluate the MSL aeroshell performance.

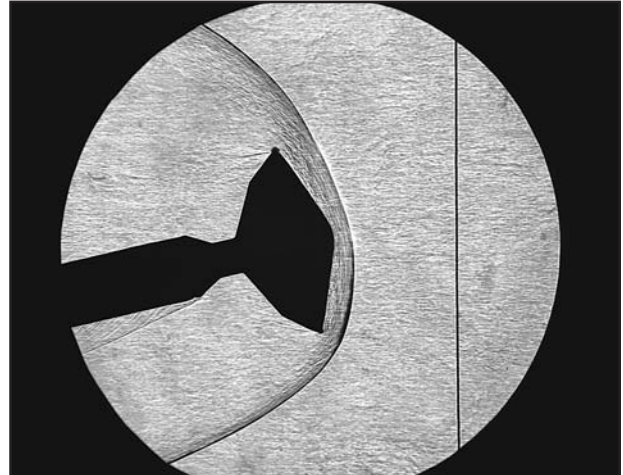
If, given the parameters of Tunnel 9 and other test facilities where NASA has collected data, the CFD code can predict the results obtained

## Characteristics

**Largest Martian Rover to Date**

**Planned Launch:** Fall 2011

**Arrival:** 2012



Above, a 1/30 scale model of the aeroshell configuration for the Mars Science Laboratory at AEDC's Hypervelocity Wind Tunnel 9 Facility. Right, a Schlieren image shows the density gradients in the laminar/turbulent boundary layer of the aeroshell configuration.

during testing, NASA will have a better idea of how well the codes can predict the performance of their aeroshell in the Martian atmosphere.

By late 2007, the National Full-Scale Aerodynamics Complex (NFAC) had resumed its historic role in supporting space exploration with the successful dynamic loads and developmental testing of MSL's massive parachute.

The last test before NFAC was mothballed in 2003 was one on the NASA Mars Exploration Rover parachute in the 80-by-120-foot wind tunnel.

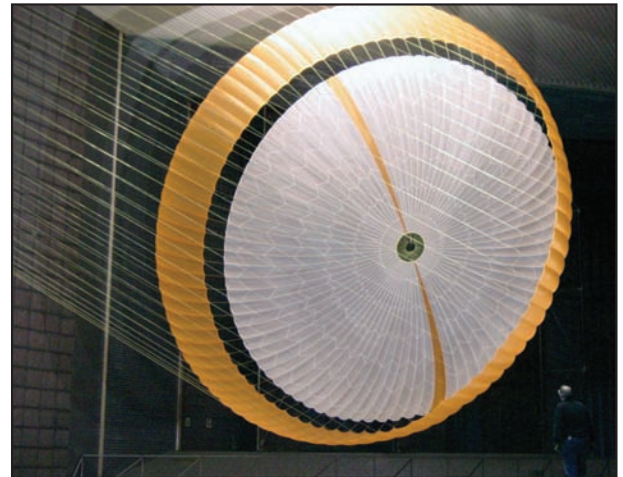
However, the significantly larger size, mass and weight of the MSL payload and the forces acting upon its large parachute were unprecedented. NASA's Jet Propulsion Laboratory, (JPL), located in Pasadena, California, chose the unique environment of NFAC for conducting the recent tests. NFAC has the world's largest wind tunnel, offering a controlled environment that is preferred over aerial drop testing.

When the second round of tests was concluded, it was clear that the parachute had survived most of the rigors of descent through the Martian atmosphere as simulated in the tunnel.

Earlier in the fall of 2007, a series of "early entry tests" at NFAC were run on the parachute to help set test conditions and determine what supporting hardware and data collection systems would be needed for the subsequent test work.

JPL, which is developing and building MSL, had three main objectives for the earlier test series.

One was to determine if the parachute would fly in the tunnel in a stable manner and to verify the functionality of the test support hardware. The second was to measure the response of the tunnel itself to the presence of the parachute, as it blocked 25 percent of the tunnel area and



An engineer is dwarfed by the parachute built by Pioneer Aerospace, South Windsor, Connecticut, which holds more air than a 3,000-square-foot house and is designed to survive loads in excess of 80,000 pounds. It has 80 suspension lines, measures more than 65 feet in length and opens to a diameter of nearly 55 feet. It is the largest disk-gap-band parachute ever built and is shown here inflated in the test section with only about 12.5 feet of clearance to both the floor and ceiling of NFAC. The parachute is attached to a launch arm mounted on a swivel base that allows the test item to pitch and yaw under simulated conditions of entry into the Martian atmosphere.

there was a risk that it could cause excessive stresses in the fan blades that drive the tunnel. The third was to practice operations and plan for the mortar-fired deployments needed in later testing.

Building on the success of the two rover geologists that arrived at Mars in January 2004, NASA's next rover mission is being planned for travel to Mars in 2011-2012.



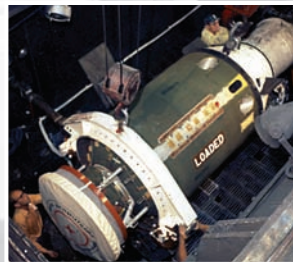
# Missile Systems



Titan



Peacekeeper



Minuteman



Tomahawk

# Missiles Systems Overview

As the nation moves deeper into the 21st century, AEDC continues to be firmly positioned to continue to support the testing of rocket motors and missile systems.

The center has had an unique capability for testing and evaluating rocket engines under simulated altitude conditions for more than 40 years, and, during that time, has tested more than 3,000 engines, from small STAR motors to large liquid-propellant engines like the Saturn IIB.

Additionally, missile systems like Air-Launched Cruise Missiles (ALCM) and Submarine-Launched Ballistic Missiles (SLBM) have seen numerous hours in both wind tunnels and engine test facilities. Other systems, like the Pershing, Sergeant Missile, Snark and Nike, have also spent time in center facilities.

In 1994, the J-6 Rocket Test Facility came online and significantly expanded the center's capability to test the large and detonable solid rocket motors that will extend the life of the existing Intercontinental Ballistic Missile (ICBM) force through 2020.

To meet the growing test requirements resulting from increased use of liquid-propellant space boosters, the center returned to testing large liquid storable and cryogenic-propellant rocket engines after a hiatus of nearly 20 years.

The center played a key role in keeping the Titan IV, America's only expendable, heavy-lift launch vehicle, from being grounded by qualification testing of a new Stage II engine. The center later tested the next generation RL-10 engine also.

In the spring of 2007, the center successfully conducted its 27th test on the Peacekeeper Stage III rocket engine to determine the effect of age on the performance of the solid rocket motor. Part of America's nuclear deterrent force from 1986 to 2005, the Peacekeeper has undergone a variety of testing, including development, flight proof, qualification, production quality assurance, and aging and surveillance programs.

AEDC expanded its use of teaming agreements with rocket developers, resulting in a greater range of services and increased responsiveness to customers. For example, a teaming arrangement between AEDC, the Air Force Space and Missiles Systems Center,

Lockheed Martin, Aerojet, TRW, Brown & Root and a host of smaller contractors accomplished the complex facility preparations and test program for the Titan IV engine test program. Similarly, the first test program using the new cryogenic propellant system also involved teamwork. In each case, the teaming arrangement allowed its members to contribute their own expertise and resources to ensure a more comprehensive, faster test program to fit the customer's needs.

Supporting AEDC's vision of being the center of knowledge for simulated rocket testing, center employees have completed a number of initiatives to improve the scope and quality of products available to users. These include: statistical analysis of aging trends in solid rocket motors; hosting the Minuteman Propulsion System Rocket Engine database; advancements in liquid rocket engine health monitoring; and improved test information handling, storage and retrieval.



# Missiles Systems Timeline

## The 1950s

SM-65 Atlas

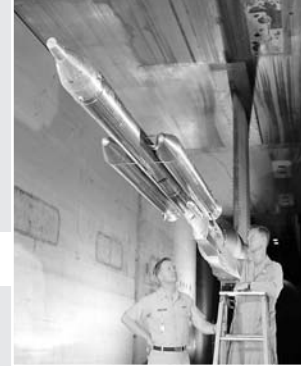
Sergeant Missile  
Snark  
Nike



Snark

Polaris SLBM

X-15  
SM-68 Titan  
LGM-30  
Minuteman



Titan

## The 1960s

Saturn V  
Little John

Thor-Delta

Patriot

Short-Range  
Attack Missile



Pershing



Sidewinder

## The 1970s

Trident SLBM

Sidewinder

AIM-9

Poseidon SLBM

Pershing

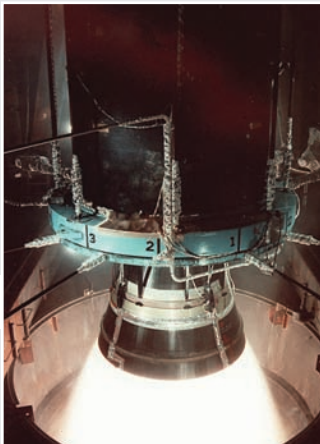
Maverick

Walleye

BGM-109  
Tomahawk

Air-Launched Cruise Missile

AMRAAM



Peacekeeper



AMRAAM

## The 1980s

Peacekeeper

## The 1990s

Exoatmospheric Kill Vehicle  
Aegis  
National Missile Defense

THAAD  
Standard Missile-3  
PAC-3

## The 2000s

Kinetic Energy Interceptors

Ground-based Midcourse Defense

# SM-65

## Atlas

The Atlas ballistic missile began with a U.S. Army Air Corps request for proposal in October 1945. The Atlas missile became the first operational intercontinental ballistic missile in America's nuclear arsenal and represents the beginning of the U.S. Space Program. The Atlas, operational in the late 1950s, evolved into a space launch vehicle and was used to launch commercial and military satellites and other space vehicles. In September 1955, faced with intelligence reports of Russian progress on their ICBM, the Atlas received the highest national development priority. The project became one of the largest and most complex production, testing and construction programs ever undertaken.

### Characteristics

**Primary Function:** ICBM

**Contractor:** Originally built by the Convair Division of General Dynamics

**Power Plant:** (ICBM/Atlas D): Two Rocketdyne LR105-NA strap-on boosters and one Rocketdyne LR89-NA-3 plus two small vernier rockets for attitude correction

**Length:** 82.5 feet

**Weight:** 267,136 pounds

**Diameter:** 10 feet

**Range:** more than 6,300 miles as an ICBM (the Atlas D could achieve orbit)

**Maximum Speed:** Orbital velocity of about 17,500 miles per hour (approximately 16,000 miles per hour as an ICBM)

**Ceiling:** Maximum altitude: varied by orbital track (approximately 900 miles as an ICBM)

**Warhead:** Nuclear warhead on ICBM, none on scientific or Mercury flights

**Date Deployed:** September 1959



### Highlights of Development Testing at AEDC

- Nose cone configuration
- Base recirculation
- Shape
- Base heating
- Upper-stage motor

AEDC began supporting the development of the Atlas missile prior to its becoming operational. In 1956, tests of nose cone configurations in support of the Atlas Intercontinental Ballistic Missile (ICBM) program began in Tunnel E-1. A year later, the Atlas nose cone was one of the first two test programs to be tested in the center's 16-foot transonic wind tunnel (16T).

Atlas ICBM base recirculation effects were studied in 1958 in the center's 40-inch supersonic tunnel using a scale model missile equipped with small rocket engines.

At the Astronautic Vehicle Session of the Third Air Force Office of Scientific Research (AFOSR) Astronautic Symposium, Oct. 12, 1960, in Los Angeles, California, Brig. Gen. Homer A. Boushey, then Commander of AEDC, commented on the importance of the work on the Atlas program completed by AEDC:

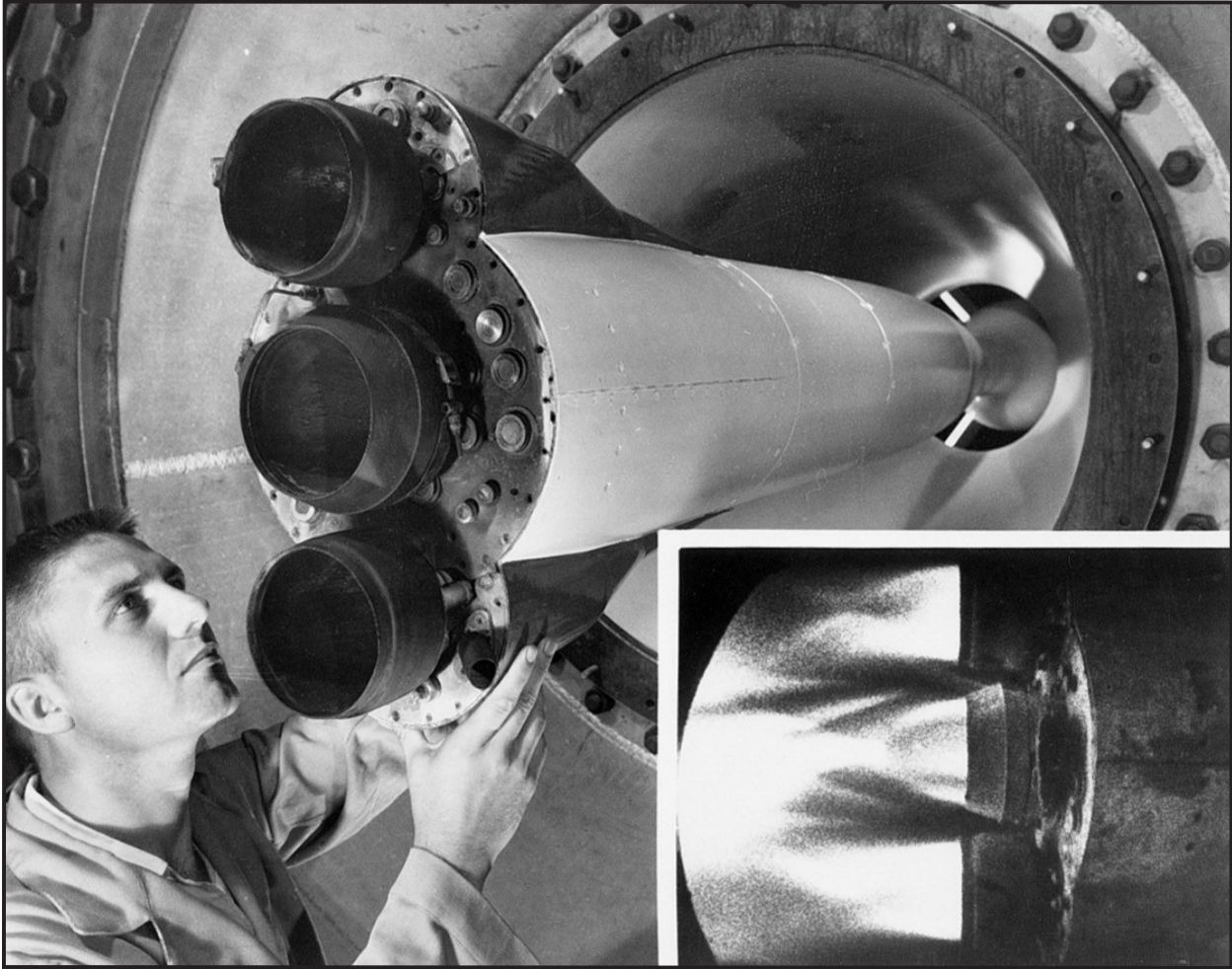
*"Although testing of rocket motors is a major part of our current work at the Arnold Center, we also are doing significant work in aerodynamic areas. Arnold has, from the beginning, conducted many tests on operational nose cones to obtain data on heat transfer, pressure distribution and forces during reentry. Among the first tests were those on early configurations proposed for Atlas, Titan, Thor and Polaris...*

*"BMD requested tunnel tests to measure static pressures over the second and third stages of a 7-percent scale model of the vehicle after structural failure of the payload fairing on the second Atlas-Able launch attempt last November. Similar measurements were made over the first and second stage transition section and unsteady pressures were measured on the third stage.*

*"The tests were on two configurations. One was – Atlas-Able IV – a hemisphere-cone-cylinder configuration used in the November launch. The second was an ellipsoid-cylinder Atlas-Able V.*

*"In comparing the data obtained in the two tests, it was found that the unsteady pressures on the ellipsoid-cylinder configuration – Atlas-Able V – had lower peak amplitudes than those on Atlas-Able IV. The Atlas-Able V configuration was used in the 25 September [1960] launch of the*





A scale model of Atlas base was used in early tests in AEDC's wind tunnels to study base recirculation at simulated altitudes. Inset is from a motion picture of a test run which recorded recirculation at various simulated altitudes.

*lunar-orbit vehicle."*

In September 1962, NASA's Mariner 2 spacecraft was on a looping 180-million-mile flight path to probe the planet Venus. During the years prior to the launch, extensive work had been done to ensure the flawless operation of the Atlas missile propelling the probe vehicle. Tests at AEDC had helped solve a base-heating problem in the Atlas booster; checked the transonic flight characteristics of the booster vehicle; and determined that the "ullage" rockets would fire correctly just prior to ignition of the upper-stage propulsion vehicle. (Solid ullage rockets shove the satellite vehicle forward and "seat" the liquid propellants in their tanks to ensure ignition.) Center tests also had checked the ability of the upper stage to cut off, coast and re-ignite after a period of simulated orbital coasting; accurately determined the specific engine thrust under simulated altitude conditions; and, determined that the upper-stage rockets would operate at high vacuum conditions.

Test data confirmed NASA reports following the launch, which described the operation of the various rocket stages as "excellent." The validity of the tests at AEDC also was

confirmed in many respects when it was compared with the data telemetered back to Cape Canaveral after the actual launch.

In March 1972, NASA's Pioneer F interplanetary space probe began a 22-month journey to examine Jupiter at close range. The launch represented a high point in a year-long association between AEDC's Engine Test Facility (ETF) and the launch vehicle's third-stage rocket motor. Officially designated the TEM-3644 by its manufacturer Thiokol Chemical Corp., the Delta stage-solid propellant motor underwent a prolonged series of development and flight qualification tests in Propulsion Development Test Cell T-3 in preparation for its first flight aboard the Atlas-Centaur booster.

Seven motors were fired during the development phase, and an additional five were fired in flight qualification.

The motor was programmed to deliver an average thrust of 15,000 pounds during a 44-second burn. So that it would be able to maintain stability, the engine was designed to spin while firing. Tests were conducted at spin rates ranging from 30 to 150 revolutions per minute, and



Atlas ICBM base recirculation effects were studied in 1958. The tests were conducted in the center's 40-inch supersonic tunnel using a scale model missile equipped with small rocket engines.

motor ignition was accomplished at simulated altitudes up to 120,000 feet. While the Pioneer mission was the first flight for this motor, the TEM-3644 is a descendent of the motor previously used in the Surveyor program and as the third stage in the later models of the Thor launch vehicle.

Development of reliable reentry vehicles was aided by a new instrumentation technique developed in the von Kármán Gas Dynamics Facility (VKF). Called photographic pyrometry, the system is used to record surface temperatures on reentry models flying at speeds up to 12,000 mph through the 1,000-foot-long aeroballistic G Range. The procedure made it possible to take a high-speed photograph of a glowing model and translate the photographic image through computer processes into a detailed map that shows the pattern of high temperatures on the model's surface. The technique provides a better understanding of aerodynamic heating and the manner in which ablative coatings used for heat protection burn and erode. Test data supplement those data obtained with a high-speed laser photographic system previously perfected in VKF, which shows the rates at which ablative material is removed during simulated reentry.

Years later, the candidate fixed-foam insulation (FFI) materials for use on Atlas Centaur launchers were evaluated under aerodynamic heating conditions in the center's wind tunnels. The Air Force used the Atlas Centaur to launch payloads into orbit beginning in 1991.

Test information helped the development of the FFI system, intended to replace the legacy system of jettisonable, fiberglass insulation panels for the liquid hydrogen propellant tank sidewalls. According to test engineers, the FFI system is more reliable and costs less than the jettisonable panel system. The system also gives the Atlas Centaur an increased payload capability.

Data from the tests helped in the selection of materials for the insulation system and also enhanced the computer code used by General Dynamics, the Atlas Centaur manufacturer, to predict material performance. The tests were conducted in AEDC's aerothermal supersonic wind tunnel at an airflow speed of Mach 4. Required air temperatures in the tunnel were achieved by introducing air from electric and natural gas-fired heaters.

Candidate materials were tested one at a time by placing a piece of the material in a recessed area of a 12-by-34-inch wedge attached to a sting in the tunnel. To make material changes, test material was lowered into a model injection room beneath the tunnel where technicians made the changes and then raised the sting and wedge back into the same air conditions as before.

The wedge was instrumented with high-temperature heat-transfer gauges to define the surface heating upstream of the material samples. The surface temperature of the wedge-mounted material samples was measured using infrared photography.

# SLBM

## Submarine-Launched Ballistic Missiles

*Submarine-launched ballistic missiles (SLBMs) have been an integral part of the U.S. strategic deterrent for six generations, starting in 1956. Each generation has been continuously deployed at sea as a survivable retaliatory force and has been routinely operationally tested and evaluated to maintain confidence and credibility in the deterrent.*



### Highlights of Development Testing at AEDC

#### Characteristics

##### Trident II

**Primary Function:** SLBM  
**Contractor:** Lockheed  
**Power Plant:** Three-stage solid-propellant rocket  
**Length:** 44 feet  
**Diameter:** 6 feet, 11 inches  
**Weight:** 130,000 pounds  
**Range:** >4,000 nautical miles  
**Date Deployed:** 1990

##### Poseidon

**Primary Function:** SLBM  
**Contractor:** Lockheed  
**Power Plant:** Thiokol/Hercules engines  
**Length:** 34 feet  
**Diameter:** 6 feet, 2 inches  
**Weight:** 64,400 pounds  
**Range:** 2,880 miles  
**Date Deployed:** 1970

##### Polaris

**Primary Function:** SLBM  
**Contractor:** Lockheed  
**Power Plant:** Aerojet solid-fueled rocket  
**Length:** 28 feet, 6 inches  
**Diameter:** 4 feet, 6 inches  
**Weight:** 28,800 pounds  
**Range:** 1,200 nautical miles  
**Maximum Speed:** 8,000 mph  
**Date Deployed:** 1960

- AEDC's Tunnel 9 built specifically for testing SLBMs
- Polaris reentry problems analyzed in Tunnel F
- Polaris nose cone tested in 16T
- Heat-transfer tests performed in Tunnels A, B and C for reentry vehicle portion of the Poseidon
- Trident's upper stage tested in J-5 to verify ignition and performance characteristics
- Wind tunnel tests conducted to determine how to reduce drag on Trident

Submarine-launched ballistic missiles (SLBMs) have been an integral part of the strategic deterrent for six generations, starting in 1956 with the U.S. Navy Fleet Ballistic Missile (FBM) Polaris (A1) program.

Since then, the SLBM has evolved through Polaris (A2), Polaris (A3), Poseidon (C3) and today's force of Trident I (C4) and Trident II (D5). Each generation has been continuously deployed at sea as a survivable retaliatory force and has been routinely operationally tested and evaluated to maintain confidence and credibility in the deterrent.

AEDC's Hypervelocity Wind Tunnel No. 9 Facility, commonly known as Tunnel 9, shares a common factor with AEDC in that they both were beneficiaries of German wind tunnel technology; Tunnel 9 received two German wind tunnels.

The Army Air Corps said they were going to take all the wind tunnels, but Navy officials asked why they couldn't have some of the technology also. The Navy received Tunnels 1 and 2, the predecessors to Tunnel 9.

In July 1945, the U.S. Joint Chiefs of Staff awarded custody of Tunnels 1 and 2 to the U.S. Navy. They were then passed from the Chief of Naval Operations to the Bureau of Ordnance and then to the Naval Ordnance Laboratory.

The tunnels helped initiate a fledgling U.S. supersonic research

## Submarine-Launched Ballistic Missiles



**Early tests were conducted in 16T to solve major Polaris base heating problems. Theoretical and experimental studies by contractor personnel succeeded in discovering a new base flow pattern and a previously unknown base heating source. Systematic testing succeeded in developing a missile base configuration that keeps the base heating under control. These findings were subsequently applied to the design of the Minuteman, the Titan and the Centaur systems.**

program. Tunnel 1 (T-1) is still located at the Tunnel 9 complex and was used as a calibration lab up until about 1996.

In the 1960s and 1970s, the Navy felt there was a need to develop hypersonics to support the reentry phase of their SLBM program.

The importance of developing the hypersonics is fairly easy to understand. When a reentry body carrying a nuclear warhead, for example, is coming in from space, it is moving at 25,000 feet per second. It is imperative to know that the reentry body will hit a specific spot and destroy it. AEDC's Tunnel 9 was developed to mature those reentry targeting systems.

Testing of SLBMs at AEDC began in 1957 with the Navy's Polaris program. Chief challenges of the Polaris were stability and missile base overheating. Propulsion Wind Tunnel [PWT] personnel had to design and build the equipment required to test these issues. In the late 1960s, testing began on the Navy's new Poseidon missile which would replace the Polaris. The Poseidon's second-stage rocket motor was the largest solid-fueled rocket fired at a simulated altitude above 100,000 feet at that time. By 1967, AEDC was testing the Trident missile (also Navy) to verify ignition and performance as well as to reduce drag and increase range

For the next 30 years, AEDC would contribute to the development of the Navy SLBMs. The Trident missile would be tested in rocket test cells J-4, J-5 and J-6, the Decade facility, PWT's 16-foot transonic wind tunnel (16T), Tunnel F and the H-1 Arc Heater facility. Many of the tests conducted at Arnold on the various SLBMs used

capabilities not available anywhere else in the world.

### **Polaris**

Polaris was the first SLBM deployed by the Navy. Built during the Cold War, the Polaris had a nuclear tip and was designed to be used as a nuclear deterrent.

In September 1959, the first Polaris A-1X prototype missile, which included an inertial navigation system, was successfully launched.

At AEDC in 1957, the center's Tunnel F, also known as the "Hot Shot" tunnel, was used for the first time during the Polaris testing to analyze aerodynamic reentry problems.

Late in 1959, Lockheed and the Navy scheduled a test program for June 1960 in 16T for a proposed nose cone for the Polaris fleet ballistic missile.

Although the center had done considerable work in support of Polaris in three different facilities, the nature of these tests, which involved stability, posed a problem.

Normally, this type of test is performed to determine the degree of stability of a nose cone – does it oscillate or wobble? If so, how much oscillation occurs at various velocity/altitude conditions? If there is oscillation, does it tend to diminish and cease, or does it tend to increase to the extent that the nose cone tumbles end over end until it either destroys itself or goes into such an erratic trajectory that it misses the target?

The nose cone is mounted in the test section on what is called a free oscillation balance system. Airflow is started through the tunnel, and the amount of oscillation, if any, is recorded by the instrumentation system at various Mach numbers and altitude conditions.

However, these were not to be routine stability tests. Stability of the model was already known to be questionable. What test engineers wanted to know was how questionable the model stability was. And thus arose the need for a forced oscillation system, which, overly simplified, is a system to control the oscillation (as opposed to free oscillation, which can become destructively violent) and prevent possible destruction of the model and the model support.

Unfortunately, there was no forced oscillation system available at AEDC. Two years earlier, in 1952, PWT management had explored purchasing a forced oscillation dynamic balance system for tests of this kind and even sent requests for bids to fabricate a system to outside firms. However, because the only bids received ranged from \$150,000 to \$250,000, and because there were no tests



**Hercules Poseidon second stage model undergoes testing in the J-5 test cell in 1968.**

foreseen that would require the system, in that time of tight budgets the project was put on the shelf until January 1960.

The test program that Lockheed and the Navy wanted to run in 16T was vital to the Polaris program, and a forced oscillation system was vital to the test program; but there was neither time nor money to have one made by an outside commercial firm. Thus, it was decided to design and fabricate the system at the center in the PWT modifications section.

For all practical purposes, the starting point on this fabrication project was zero. There was only one known system that was even close to the requirements and that was at the NASA's Ames Lab in California.

Although it was much too small for the 16T requirements, it was the only place to start. Using the Ames system as a model, PWT personnel began design work in January 1960 and blueprints were sent to the PWT Model Shop in March.

Tolerances involved were as small as 3/10,000 of an inch or 1/10th the thickness of a piece of paper, a major challenge for AEDC machinists, and system fabrication had to be accomplished with a special helicopter grease. Nevertheless, the system was successfully finished on time and installed in 16T with the nose cone on it for testing in June.

The Polaris returned to AEDC in 1962, when its early launchings resulted in several total losses caused by unexpected overheating of the missile base, and AEDC personnel were called upon to help determine the cause of the overheating. Theoretical and experimental studies succeeded in discovering a previously unknown base flow pattern and base heating source. Systematic testing of specific Polaris missile base configurations in conjunction with extended general studies succeeded in developing a missile base configuration that kept the base heating under control. These findings were subsequently applied

to the design of the Minuteman, the Titan and the Centaur systems.

### Poseidon

The Poseidon missile was the second U.S. Navy ballistic missile system and was powered by a two-stage solid-fuel rocket. In 1967, AEDC conducted aerodynamic heat-transfer tests on the reentry vehicle portion of the Poseidon in Tunnels A, B and C.

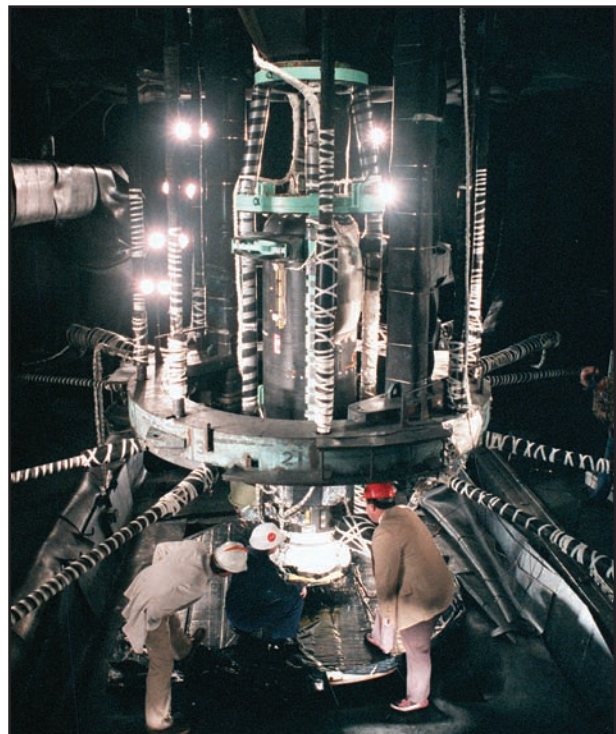
Later, in May 1968, the first second-stage rocket motor for the Navy's Poseidon missile was fired in the J-5 test cell. This was the largest solid rocket fired at simulated altitudes above 100,000 feet.

The test required a new exhaust diffuser, one that could withstand extremely high temperatures, higher than any previously encountered in the testing of solid-propellant rockets at AEDC. Four firings of the Poseidon motor were conducted using this diffuser.

The Poseidon succeeded the Polaris missile beginning in 1972.

### Trident

The Navy's Trident missile is armed with nuclear warheads and is launched from nuclear-powered ballistic missile submarines. Trident missiles are carried by 14 active U.S. Navy Ohio class submarines and, with British warheads, four Royal Navy Vanguard class submarines. Trident I (C4) was deployed in 1979 and phased out in the 1990s and early 2000s. Trident II (D5) was first deployed



**A Trident rocket motor is prepared for testing in J-4.**

## Submarine-Launched Ballistic Missiles

in 1990 and was planned to be in service for the 30-year life of the submarines until 2027.

In 1970, the Trident's upper stage rocket motor was tested in the J-5 test cell to verify ignition and performance characteristics at flight pressures and temperatures.

Changes in the original design of the submarine-launched missile induced additional drag and thus decreased its range. In 1974, wind tunnel tests were conducted to help determine how to reduce the drag on the Trident and thereby increase its range.

These AEDC tests involved a proposal to equip Trident with an aerodynamic spike that would detach the shock wave from its normal position, where it induces additional drag, and let it reattach farther aft on the body.

The purpose of the wind tunnel tests was to obtain heat-transfer and pressure distribution data in the shock wave reattachment region at flight conditions simulating speeds between Mach 1.75 and 5.25 (120 to 400 mph) and altitudes from 40,000 to 100,000 feet.

In 1974, a series of 38 firings of subscale rocket motors – part of the design effort on the submarine-launched Trident missile – was completed at the center.

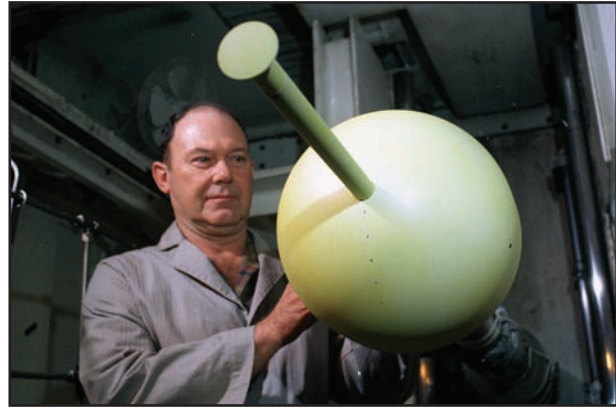
Each of the firings, which generated up to 3,600 pounds of thrust apiece, examined a different nozzle design. Data from the test series would be considered in arriving at a final design of nozzles for the upper two stages of the three-stage missile.

The test, conducted for the Navy and Hercules-Thiokol, motor subcontractor for all three Trident stages, required more than two months to complete. All 38 motors were tested at simulated altitudes of 100,000 feet or higher.

The next year (1975), AEDC personnel performed wind tunnel tests to examine deployment of a mechanical device that changes the aerodynamic shape of the Trident. The telescoping aerospike, extended explosively after the missile emerged from the ocean for the airborne portion of its flight, and causes the blunt-nosed Trident to behave aerodynamically, like a pointed missile. The AEDC tests were conducted by mounting a full-scale nosecap on the scavenging scoop of 16T.

Normally the scoop is used to remove combustion products from the closed-loop tunnel during jet or rocket engine tests. It was adapted into a support structure because of the size and weight of the nosecap. On the floor of the tunnel were an extended aerospike assembly and one in the retracted position as it is fitted into the nosecap during the underwater phase of its flight.

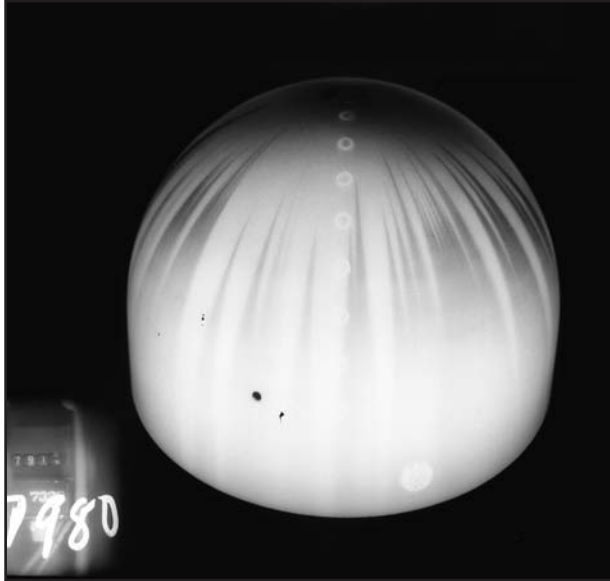
In that same year, AEDC completed a five-motor test series supporting development of an exhaust nozzle for the Navy's Trident ballistic missile in which nozzles of various contours were fitted to 30-inch-diameter boilerplate motors loaded with high-energy propellants to examine the effect of the contours on delivered specific impulse. Also in 1975, AEDC engineers conducted tests to aid the Navy



A scale model of spike-equipped Trident missile forward section is prepared for tests in a supersonic wind tunnel. Tests were run to obtain heat-transfer and pressure distribution data in the shock wave reattachment region on the missile body after it is separated from the forward region by the spike.



Wind tunnel tests to examine deployment of a mechanical device that changes the aerodynamic shape of the Trident missile was completed in 1975. The AEDC tests were conducted by mounting a full-scale nosecap on the scavenging scoop of 16T. Normally the scoop is used to remove combustion products from the closed-loop tunnel during jet or rocket engine tests. It was adapted into a support structure because of the size and weight of the nosecap. On the floor of the tunnel are an extended aerospike assembly and one in the retracted position as it is fitted into the nosecap during the underwater phase of its flight.



Photographic techniques were used in wind tunnel tests of the Navy's Trident missile at AEDC. The aerodynamic spike was removed for one run during the test program, leaving a hemisphere. The black and white thermographic phosphor data photograph obtained during this run exhibited an unusual boundary-layer transition pattern. The dark streaks are hot relative to the lighter areas and represent the pattern. The dark color analysis of the black and white photograph further clarifies the regions of laminar and turbulent flow.

in formulating range safety procedures for forthcoming Trident missile launches. Components were used in the wind tunnel tests to obtain aerodynamic data at angles-of-attack up to 180 degrees. These measurements, coupled with other information, enabled the Navy to ensure that adequate launch corridors are established should an unsuccessful launch occur.

It would be more than 20 years later when the Trident would make a return trip to AEDC. In 1998, AEDC's then newest test facility – Decade – provided data to ensure viability of the nation's major nuclear deterrent system.

For several years, the Navy Strategic Systems Project office sponsored component testing to verify that cables used to carry signals in the missiles can withstand conditions they will be exposed to in a nuclear environment. These tests will ensure that our nation's weapons could survive and still perform their mission in a radiation environment resulting from a nuclear explosion.

Decade team members used a Modular Bremsstrahlung Simulator to generate high-intensity electrical beams which hit a metal target and generate X-rays pulses simulating those produced by a nuclear explosion. The simulator projects the X-rays onto the cables, where sensors obtain readings on cable responses. These readings would be used to determine whether the cables were manufactured to proper specifications to withstand the radiation conditions they would be exposed to in a nuclear environment.



Six different models of Trident components, or combinations of components, were used in the wind tunnel tests to obtain aerodynamic data at angles of attack up to 180 degrees. These measurements, coupled with other information, enabled the Navy to ensure that adequate launch corridors are established should an unsuccessful launch occur.

The entire process is similar to getting a dental X-ray except that a few thousand times more X-rays are produced. The entire process takes only 40 billionths of a second to complete but produces vast amounts of data that are used to determine how these cables react to various levels of X-rays.

In 1999, AEDC's arc heater facility was supporting the Trident missile program. Nosedip material qualification tests completed in the H-1 Arc Heater facility helped to develop new materials for the Trident.

Test data would be used to qualify candidate nosedip materials scheduled for flight testing and incorporation into the operational missile system.

Materials developed in arc heater ground tests at AEDC are essential components of the thermal protection system for the Trident. Fabrication and qualification of many reentry vehicle thermal protection materials today has to be done from 'square one' since most of the previously existing nosedip and heatshield materials are no longer made. Ground test data correlation with reference materials from previous tests is critical to our customers to ensure the new materials perform as well as the originally specified materials.

In April 1999, test crews completed four test runs as part of the Navy's Reentry Systems Application Program ground test effort to screen and qualify candidate reentry nosedip materials for the Trident missile.

During the runs, the team tested 23 candidate nosedip material samples at high stagnation heating and pressure conditions to simulate flight conditions the missile would experience during a mission.

Test objectives included evaluating nosedip materials for upcoming Navy flight testing and evaluating two new nosedip test techniques for suitability in future testing.

# SM-68

## Titan

*The Titan I was the United States' first true multistage ICBM. The program began in January 1955 in parallel with the Atlas program. The Air Force's goal in launching the Titan program was twofold: to serve as a backup should Atlas fail and to develop a large, two-stage missile with a longer range and bigger payload that also could serve as a booster for space flights.*

*Titan I was a two-stage, liquid-fueled, rocket-powered missile; Titan II incorporated significant performance improvements over the Titan I. Phase out of the Titan I weapon system was completed in 1965, and Titan II deactivation was completed in 1987.*

*The Titan III was initially developed to support the X-20 Dyna-Soar and Manned Orbiting Laboratory (MOL) programs. It then, along with the Titan IV, served for years as the U. S. Air Force's heavy-lift space launch vehicle until replaced by the Evolved Expendable Launch Vehicles (EELV).*



### Highlights of Development Testing at AEDC

- More than 350 test engine firings for the Titan system
- Cradle-to-grave testing of Titan IV launch vehicle
- Testing of multiple booster configurations

Since the late 1950s, the Titan-Centaur combination has carried some of the nation's most important missions, such as the Viking probes to Mars and the Voyager probes to the outer planets. AEDC, the only collection of facilities in the world capable of testing large rocket engines at altitude conditions, has been crucial to those missions

Over the ensuing 30 years, AEDC has conducted more than 350 motor firings for the Titan system. The latest testing occurred in Rocket Development Test Cell J-4 when the test team validated the reliability of the nozzle skirts for Pratt & Whitney's (P&W) new 105,000-pound-thrust quartz engine, the RL-10B.

AEDC provided cradle-to-grave support for the heavyweight Titan IV launch vehicle. The launch of a Titan rocket on Sept. 9, 2003, was the final Titan flight after 30 years of service and left only three unused Titan IV rockets in the fleet. The rockets were replaced by newer technology.

With the introduction of the Evolved Expendable Launch Vehicle (EELV) for the Air Force space launch system, vehicles such as the Delta, Atlas and Titan have been replaced with a more affordable family of space launch vehicles.

AEDC's support began in 1958 when center employees test fired their first Titan solid-propellant rocket motor in engine test cell T-4 and their first liquid-propellant rocket, using a scale model Titan in the 16-foot transonic wind tunnel (16T). A year later, it was another first.

This time it was a liquid-fueled rocket engine that had been tested in

### Characteristics

**Primary Function:** ICBM

**Contractor:** Lockheed Martin

**Power Plant:** First stage: Aerojet LR87; second stage Aerojet-General LR91 engines

**Length:** 103 feet

**Weight:** 270,000 pounds

**Diameter:** First stage - 10 feet; second stage - 8 feet

**Range:** 6,300 statute miles

**Maximum Speed:** 15,000 mph

**Maximum altitude:** 700 statute miles

**Crew:** None

**First Launch:** Feb. 6, 1959



a closed circuit wind tunnel with the Phase III portion of the Titan test program.

In the fall of 1960, AEDC initiated a test program in the Test Cell T-1 to investigate a proposed technique for separating the first and second stages of the Titan II. On Oct. 31, an XLR-91 liquid-propellant engine for Titan II was fired in test cell J-3.

On March 20, 1962, a Titan II second-stage engine in test cell J-3 generated the highest total impulse ever recorded in an altitude simulation cell. Following that on April 9, the first tests of the Titan III engine tests were started in the rocket test facilities and at a simulated altitude of 44 miles.

In 1963, tests were conducted on a full-scale transtage engine for the X-20's (also called the Dyna-Soar) Titan III booster. These tests provided information on how the engine would perform at extreme altitudes and on how to verify the engine's structural durability. In addition, another test set up in support of Titan III utilized the base of the Titan II. The tests were performed to obtain data that could be used to help determine a safe technique for jettisoning the two rocket cases after their propellant had burned out.

The Titan III full-scale, flight weight production engine test began in the summer of 1964 in the J-3 test cell.

In 1963, while the Titan IIIC 470,000-pound-thrust, liquid-core rocket was being fired in test cell T-4 to confirm altitude ignition reliability prior to launch, the Titan Agena model configuration tests were beginning in 16T.

The next year, 1964, AEDC supported a Titan IIIC launch vehicle with test firings of the 8,000-pound-thrust AJ10-138 liquid-propellant rocket engine that verified that a modified oxidizer would have no adverse effect on the engine's operation in space. A compatibility problem with the standard oxidizer required that the propellant be modified by increasing the nitrous oxide content. This testing was conducted in test cell T-4. The subsequent mission was very successful and allowed for the deployment of seven separate military communications satellites and a gravity-gradient experimental satellite. This was the first time so many satellites of this type had been put into orbit by a single launch vehicle.

In 1966, a Titan III stretched-core model was tested with two, 10-foot-diameter solid rocket motors as the booster, and a 13-by-40 foot cylinder with an Apollo capsule and escape tower as the payload. The launch vehicles



**Titan III with a Manned Orbiting Laboratory (MOL) with Gemini is readied for testing in 16S.**

were subjected to large, unsteady aerodynamic forces as they passed through the transonic speed range. With the potential for deformation or bending of the entire vehicle or buffet effects on local skin panels, the tests determined the structural dynamic response (including buffet) of aeroelastic models to airloads at transonic speeds between Mach 0.6 and 1.4. This particular test was a sophisticated and unique way of utilizing the wind tunnel and would ensure the structural integrity of the various Titan III configurations.

The following year, an 8-percent scale model of a Titan IIIB standard launch vehicle for a number of Air Force satellites was one of several configurations tested in 16T to determine the effects of high-speed flight on the core engine nozzles. Compressed air was used to simulate engine and turbine exhausts, and nozzles were gimbaled up to 12 degrees to simulate flight operation at velocities between 500 and 1,100 miles an hour.

A full-scale model of a transtage Titan IIIC was tested in the Mark I Space Simulation Chamber in 1968 to verify modifications designed to improve performance. Prior to the planned early 1969 launch of the tactical communications satellite (TACOMSAT), qualification firing tests of a disposable nose-cone for the Titan III launch vehicle were completed in the aerospace simulation chamber. The full-scale tests were conducted to verify the reliability of the system by which the three-part covering was to be separated at more than 300,000 feet in its first flight, which was scheduled for January 1969. Linear

## Titan

explosive charges were used to separate the three sections of the fairing. Since explosives react differently at low pressures and since the forces acting against the sections 60 miles above the earth are far different from those at sea level, it was necessary to test the entire system at simulated altitude.

More than 30 different booster payload configurations of the Titan III were subjected to dynamic response tests in the 16T tunnel in 1969. The test articles were 7-percent scale models and included Centaur, Voyager, Gemini, Apollo, Manned Orbiting Laboratory (MOL) and other advanced payloads. Launch vehicles were subjected to large, unsteady aerodynamic forces as they passed through the transonic speed range, which might produce deformation, or bending, of the entire vehicle, or buffet effects on local B-panels. These tests determined the structural dynamic response of aeroelastic models to airloads at transonic speeds between Mach 0.6 and 1.4.

During the 1970s, AEDC conducted rocket firings in support of the aging and surveillance program for both the operational Titan II ICBM and several Titan II motors. This testing was conducted in test cell T-3 after completion of a study on rocket plume effects in January 1976.

In Mark I in January 1980, AEDC engineers began tests to demonstrate separation of a full-scale, segmented fairing – designed to protect satellite payloads during launch.

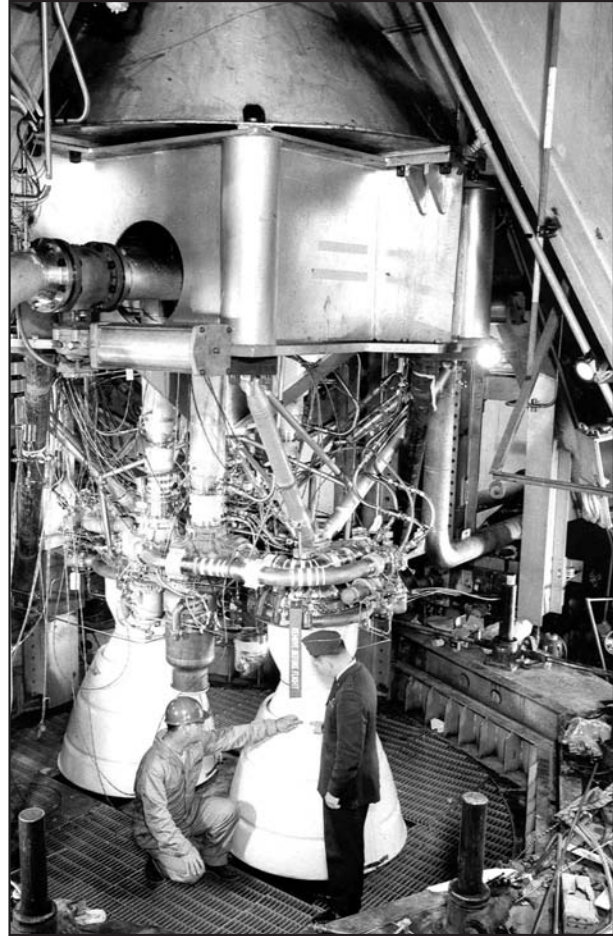
The three segments of a 55-foot-tall aluminum fairing for the Air Force's then newest satellite launcher, the Titan 34D, were separated by explosive charges and contained by an intricate system of catcher nets at conditions simulating a near-space environment of 300,000 feet. Designed by McDonnell Aircraft Corp., the fairing protects various Titan payloads from aerodynamic heating and shock as the payloads are launched through the Earth's atmosphere.

The fairing is composed of three trisectors incorporating an isogrid construction technique, which strengthens the total structure but weighs less and is less expensive than conventional fairings.

Explosive charges along the seams and at the base of the fairing separated its three trisectors cleanly during the test. New circuitry for the electro-ordnance system and all other devices associated with the fairing functioned perfectly during the test.

After separation, the fairing's trisectors, moving at a speed of about 30 mph, were contained by a radial catch system designed and fabricated by AEDC personnel. This system prevented damage to the trisectors, which can now be used in further tests.

The first payload fairing separation test for the Titan IV unmanned launch vehicle was conducted in 1988. The explosive "zipper" of the fairing was fired at simulated altitude to ensure proper separation for payload launch. The test was conducted in Mark I at a simulated altitude above 300,000 feet. It was the first full-scale separation



**This "milestone test" helped develop the Air Force's Titan III C space booster. A full-scale, 470,000-pound thrust liquid core engine was run for 92 seconds at a simulated altitude of about 100,000 feet.**

test of a 56-foot-long fairing, and the Titan IV was the largest operational expendable launch vehicle in the U.S. at that time. The vehicle was designed to deploy payloads equivalent to those of the space shuttle or heavier, placing up to 39,000 pounds into a low-Earth orbit and 100,000 pounds into a geosynchronous orbit.

Additional testing of the Titan IV launch vehicle was needed in 1989 because of an upgrade of its solid rocket motors. The upgrade included larger motors for increased payload capacity to orbit, a change from a steel casing to a stronger and lighter-weight carbon casing, and the addition of gimballed nozzles, which are more reliable for controlling the flight path of the larger Titan. The tests, performed in 16T, provided data used to evaluate the effect of aerodynamic forces and hinge movements acting on the nozzles during transonic flight. The information from the tests will be used to size the nozzle aerofairings. A 4-percent scale jet effect model of the Titan IV with and without nozzle aerofairings was used for testing.

In preparation for Titan IV second-stage nozzle testing

at simulated altitude in 1996, the J-4 Reactivation Program began. Since there had been no work involving the larger fuel quantities since the late 80s, extra precautions were taken in preparation for the testing.

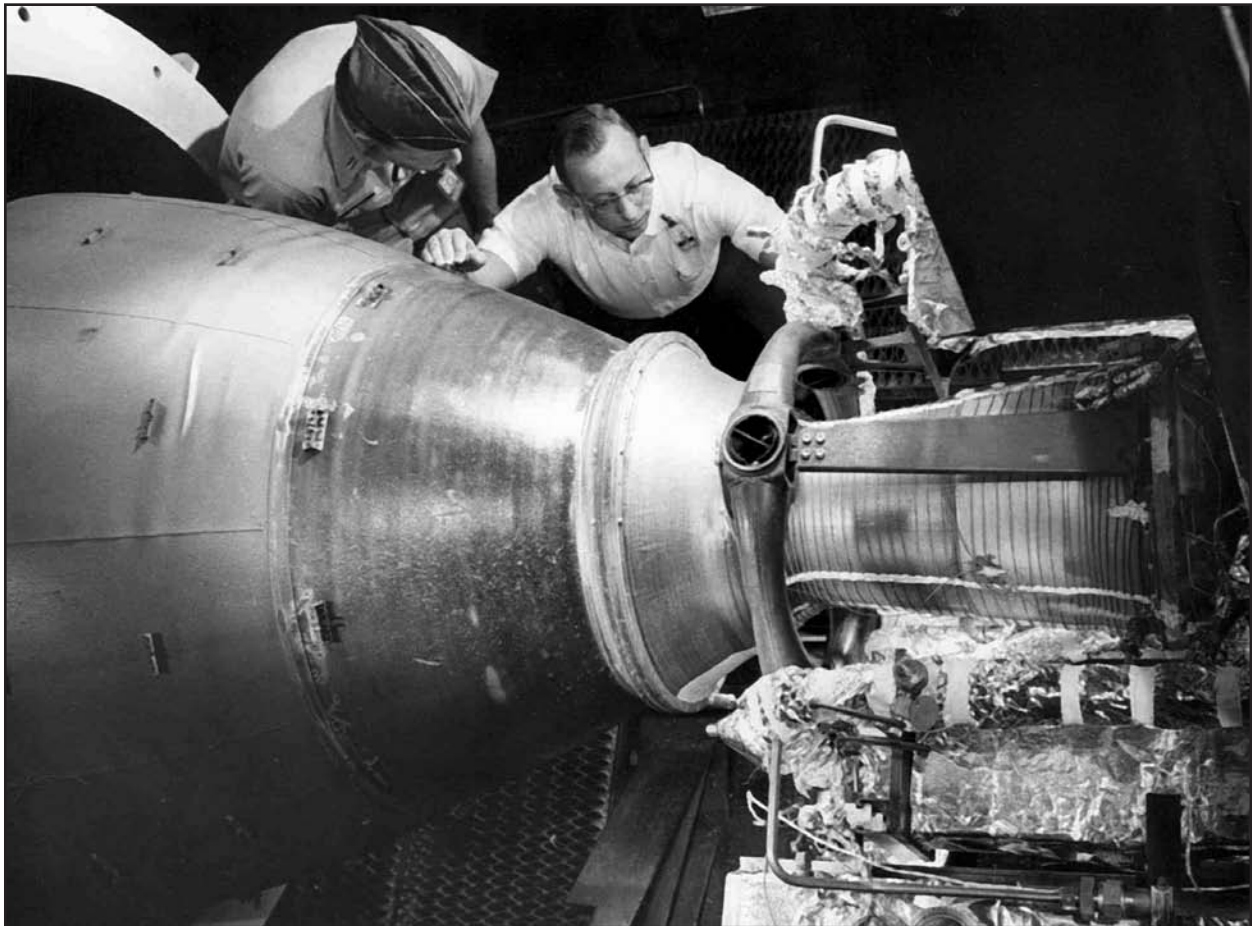
AEDC successfully validated the second-stage nozzle skirt for the Titan IV heavy launch vehicle, thus ensuring America's ability to launch critical satellites. The engine, an LR-91, burned for 300 seconds in the center's J-4 test cell, demonstrating a considerable margin for the engine, which normally burns for 232 seconds. AEDC's personnel worked extended shifts and weekends for several months preparing the facility for these tests.

AEDC performed the first qualification test of the quartz/phenolic skirt on June 1, 1996. The 105,000-pound-thrust second-stage engine burned for 274 seconds under simulated altitude conditions of more than 100,000 feet in J-4. The test successfully validated the engine's nozzle reliability.

In 1997, test cell J-4 conducted testing to validate the reliability of the nozzle skirts for Pratt & Whitney's new quartz engine, the RL-10B, which generated 105,000 pounds of thrust.



A scale model of the Titan III booster system for the X-20 Dyna-Soar manned orbital glider is mounted for testing in the Propulsion Wind Tunnel's 16-foot supersonic wind tunnel (16S) in 1963.



A Titan III Transtage rocket engine is inspected by AEDC engineers inside test cell T-4 prior to testing in 1966.

# LGM-30

## Minuteman

*The Minuteman I was a second generation Intercontinental Ballistic Missile (ICBM) that used solid propellants rather than liquid fuels. It was smaller and easier to maintain than its predecessors, and its use of solid propellants permitted almost instantaneous launch. It was designed to be maintained in, and launched from, hardened underground silos where it would be virtually immune from an enemy nuclear attack. Conceived in the late 1950s, Minuteman I was deployed in the early 1960s. Minuteman's maintenance concept capitalizes on high reliability and a "remove and replace" approach to achieve a near 100-percent alert rate. Modernization programs have resulted in expanded targeting options, as well as improved accuracy and survivability.*

### Characteristics

**Primary Function:** ICBM

**Contractor:** Boeing

**Power Plant:** Three solid-propellant rocket motors; first stage – Thiokol; second stage – Aerojet-General; third stage – United Technologies Chemical Systems Division

**Length:** 59.9 feet

**Weight:** 79,432 pounds

**Diameter:** 5.5 feet

**Range:** 5,218 nautical miles

**Maximum Speed:** Mach 23 or Mach 24 at burnout

**Ceiling:** 700 miles

**Guidance Systems:** Inertial System: Autonetics Division of Rockwell International; ground electronic/security system: Sylvania Electronics Systems and Boeing Co.

**Warheads:** One

**Date Deployed:** June 1970

**Production Cessation:** December 1978

**Inventory:** Active force, 500



### Highlights of Development Testing at AEDC

- Flight characteristics and dynamic stability testing
- Extreme altitude effects testing
- Freon replacement program testing

Today's Minuteman weapon system is the product of almost 40 years of continuous enhancement.

Testing of the Minuteman began at AEDC in 1958 and included testing of a scaled-down model of the missile in the 50-inch Mach 8 wind tunnel in the von Kármán Gas Dynamics Facility (VKF).

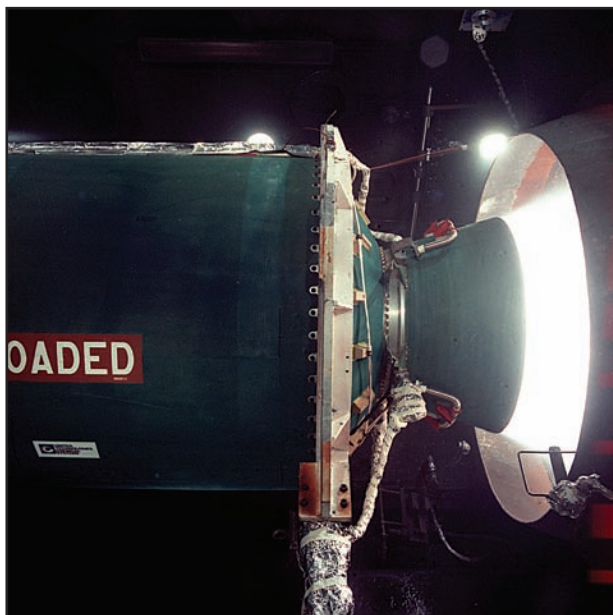
Early in 1959, the Boeing Company, as integrating contractor for the Minuteman program, provided subscale models of the missile for testing in the hypervelocity wind tunnels of VKF. Tests provided data on the flight characteristics and dynamic stability of the missile at high altitudes and high speeds.

Several solid-propellant rocket motors being considered for use in the third-stage Minuteman were successfully fired in high-altitude test cell J-2 in 1960, the first test to be conducted in the cell. To eliminate human error, a special automatic "count down" system was devised for the tests.

By 1961, AEDC's wind tunnels and test cells had been used for approximately 25 test programs in the development of the Minuteman I. More than 300 rocket motors had been fired at simulated altitude conditions. In addition, a full-scale Minuteman second stage motor was fired in the J-2 test cell.

The Minuteman was tested in the new Propulsion Development Test Cell J-2A in 1962, requiring the reversal of operation of the altitude simulation cell in order to accommodate large operating rocket motors needing altitude conditions well above 100,000 feet. The test was the highest ever for a rocket motor of its type and size. Development of Minuteman II began, although there was no environmental test cell in this country capable of testing the improved second- and third-stage motors. What resulted was the development of the Rocket Development Test Cell J-5.

In 1963, an accelerated test program of the Minuteman took place in one week, with testing of five retrorockets and four tumbling rockets. That program was followed by a full-scale Minuteman second-stage motor. In



**AEDC engineers completed simulated altitude testing of a series of three Minuteman Stage III solid-propellant rocket motors in support of the Production Quality Assurance (PQA) motor test program, and all test objectives were met. Shown above is the Minuteman Stage III motor being fired in test cell J-5.**

1964, the motor was fired as the first test in 200,000-pound-thrust capability high-altitude simulation test cell J-5.

Continued support of the Minuteman took place in 1966. Tests conducted early in the year established the quality of Stage III production motors. Extensive work was done in the second half of the year to establish the reliability of second- and third-stage Minuteman motors after extended periods of storage in the launch silos.

In 1967, tests in support of Minuteman took place in the Mark I Space Simulation Chamber. These tests involved the firing of rocket motors under extreme altitude conditions to obtain information on the freely expanding exhaust plumes. Although Mark I was not designed for this type of testing, it was adapted to the program, and 584 firings were completed within the originally scheduled time.

By the end of 1967, nearly 800 firings had taken place at the center in connection with the Minuteman program, including 60 full-scale second- or third-stage motors. Actual test cell occupancy by Minuteman components totaled more than five years.

A six-year testing program on the second-stage rocket motor of the Minuteman II Intercontinental Ballistic Missile (ICBM) began in 1968.

This program had two principal objectives. The first objective was to establish a maximum life expectancy for the motors by determining the amount of deterioration experienced while the missiles are operationally deployed in their silos. The second objective was to study effects on the motors created by various storage conditions.

The information from these tests helped to answer questions regarding replacement cycles for motors in operational missiles and improvements that could be made in their reliability or accuracy.

Tests were conducted in the J-5 high-altitude test cell.

A major phase of Minuteman testing was concluded with the test firing of 10 candidate qualification motors for the third stage of Minuteman III in July 1971. Tests of second- and third-stage motors of the several Minuteman series continued the center's support of the Aging and Surveillance (A&S) program.

Simulated altitude tests of auxiliary rocket motors for Titan and Minuteman missiles in 1972 showed that their expected useful life is three times longer than predicted. The tests provided attitude, roll, separation and reentry control data on the ICBMs. Results of the tests run to determine ignition reliability, burning rate, total thrust and structural integrity eliminated the expense of the expected replacement of thousands of the motors on the operational missiles.

Testing in Engine Test Facility (ETF) involving the fourth stage of Minuteman III, called the Propulsion System Rocket Engine (PSRE), took place in 1973. These tests also included simulating separation of the Minuteman Stage III and PSRE with the use of a computer system adapted for the purpose of keeping test techniques abreast of the increasing sophistication of missile and guidance systems.

The first of five Minuteman PSREs was subjected to dynamics testing in the Impact, Vibration and Acceleration (IVA) facility prior to static firing in 1974.

The PSRE, a prepackaged liquid rocket propulsion system, is mounted to the forward end of the third-stage Minuteman III weapons system and must provide precise impulse increments to a vehicle on a ballistic trajectory at altitudes above 300,000 ft.

The purpose of this test program was to evaluate aging characteristics of the PSRE and to predict whether the



**This nested Extendable Exit Cone (EEC) assembly is mated to a Minuteman III solid rocket motor for tests at a simulated altitude of 100,000 feet.**

## Minuteman

useful life of the system meets its one-year design specifications under operational conditions.

In IVA facility testing performed by AEDC engineers, the PSRE was subjected to the following launch-simulated dynamic environments:

1. Random Vibration – generated by an electrodynamic shaker.
2. Shock – produced by pendulum-type drop mechanism.
3. Acceleration – provided by a hydraulic drive centrifuge.

Test results defined prior to static firings showed there was no physical deterioration caused by aging.

The completion of the 100th Minuteman Missile Stage II Production Quality Assurance (PQA) test took place in 1983. From early 1971 until the milestone test, 48 Minuteman PQA tests were conducted in the J-5 test cell.

AEDC engineers “froze” the third stage of a 10-year-old Minuteman III missile “in flight” for scientific study by the Air Force Logistics Command in 1988.

Using a technique developed at AEDC in 1975, engineers ignited a shaped charge to rupture the forward dome of the motor midway through a test firing inside test cell J-5. The shaped charge opened a 16-inch-diameter hole at a simulated altitude of approximately 100,000 feet, causing a sudden decompression inside the motor and immediately extinguishing the solid fuel burn. Simultaneously, the motor was quenched internally with water to prevent the fuel from re-igniting. The result was a partially burned Minuteman third stage, which will be dissected and examined by scientists and engineers at the Logistics Command, Hill Air Force Base (AFB), Utah, as part of the Air Force’s Minuteman Reliability Assessment Program.

Since it would be impossible to shut down a Minuteman third stage at 100,000 feet and bring it back for examination, this technique proved to be the next best thing. While the sudden release of hot exhaust gases into the test cell did cause some damage, it was minimal, and the cell was ready for another test firing the following week.

AEDC was uniquely suited to perform such a test with minimal damage to either the test cell or the rocket motor because of the center’s extensive exhaust pumping facilities. These compressor plants give AEDC the only capability available to maintain extremely low pressures in test cells for long periods of time. For this test, seven exhaust gas compressors were utilized to reduce pressure in the J-5 cell from atmospheric to just under 0.2 psi and to maintain the vacuum while the Minuteman motor was firing.

Since the burn rate of solid rocket fuel is a function of the pressure inside the motor case, the sudden decompression that is achieved and maintained extinguishes the burn without a danger of re-ignition. In this case, engineers were able to reduce the internal case pressure from approximately 600 psi to approximately 2 psi in a few mil-



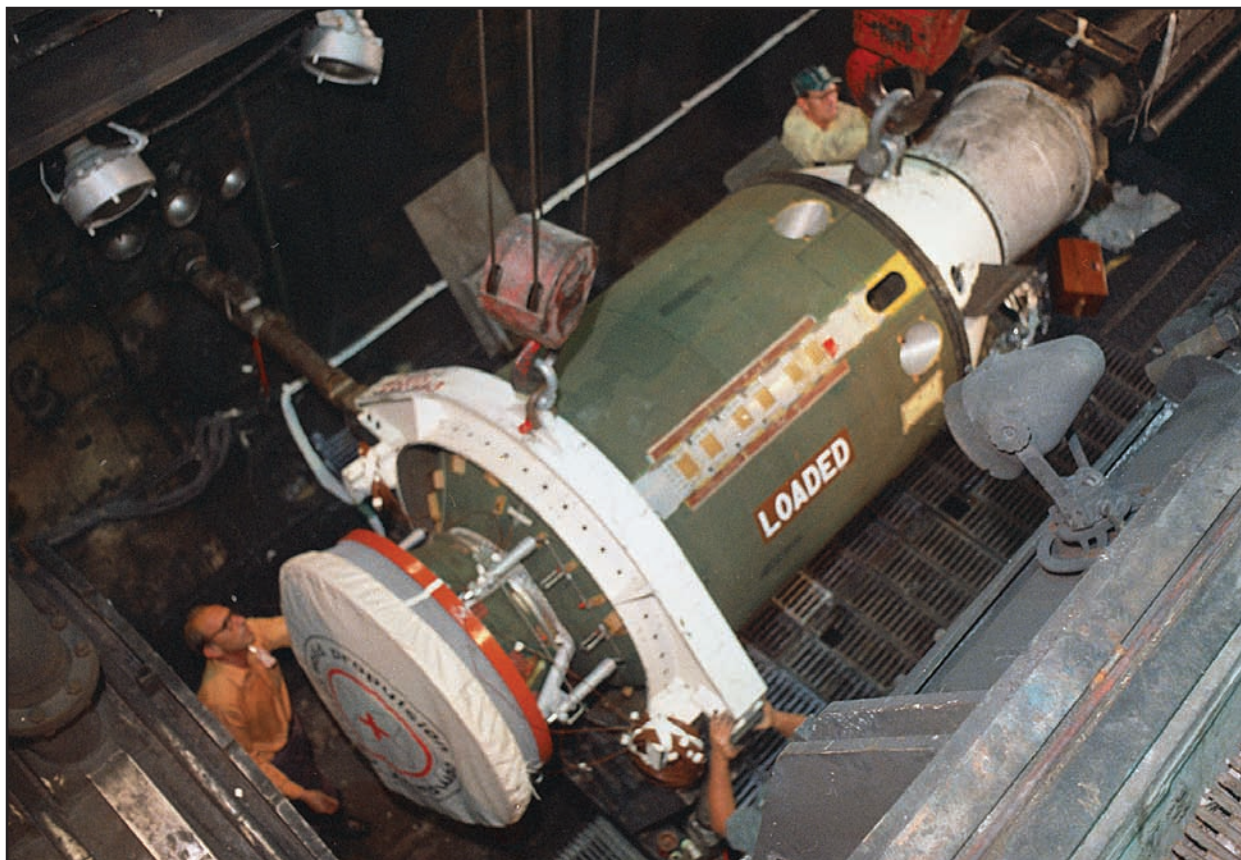
**The propulsion system rocket engine PSRE components are checked prior to simulated flight test in J-5 in 1972.**

liseconds. Previous calculations have shown this could be done by opening a 16-inch-diameter hole in the forward dome with a shaped charge.

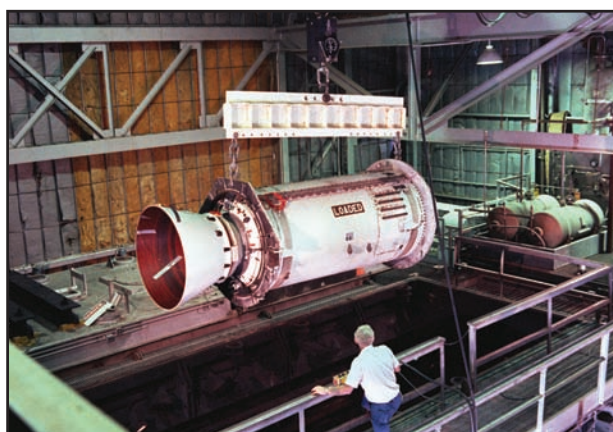
The half-burned motor and its propellant residue would allow Logistics Command engineers to examine the burn patterns and thermal insulation effectiveness of a motor that has been in an operational Minuteman silo for the past decade.

Testing to support the Minuteman Freon Replacement Program began in 1993. Freon, which was used in the Minuteman liquid-injection thrust vector control (LITVC) system, used for missile guidance, was banned after 1995 because it is one of a class of chlorofluorocarbons. The chlorofluorocarbons, when released into the Earth’s stratosphere, deplete the ozone layer. The halt of production was part of the Clean Air Act of 1994. The purpose of the program was to try to find a fluid that would give performance that is most similar to Freon and meet the required operational specifications.

In 1996, AEDC responsiveness and ingenuity saved Ogden Air Logistics Center (OO-ALC) \$30,000 when



This 40,000-pound-thrust, third-stage rocket motor for the Minuteman III ICBM is installed in one of 11 high-altitude test cells in 1972. A protective cover encloses the end of an EEC (lower left) which was evaluated as a means of increasing the motor's thrust at altitude. Three 60-second firings were conducted at conditions simulating altitudes of about 90,000 feet.



This 75,000-pound-thrust, second-stage rocket motor for the Air Force's Minuteman Intercontinental Ballistic Missile was fired in a test cell in 1978 at conditions simulating an altitude of approximately 100,000 feet. The tests conducted for the USAF's Ogden Air Logistics Center (OO-ALC), Hill AFB, Utah, were part of the Ogden-directed Long Range Service Life Analysis (LRSLA) program. This program provides data for the OO-ALC System Manager to use in assuring that the operational readiness of the Minuteman Intercontinental Ballistic Missile is being maintained.

center personnel managed to test a rocket motor and two subsystems from a different rocket motor together in test cell J-6. OO-ALC needed quick turnaround on test data to assist in making a decision regarding refurbishment of the Minuteman subsystems. AEDC's J-6 test team met the challenge and found a way to test these subsystems together with a Minuteman Stage III rocket motor already on the J-6 schedule. Also in 1996, the 116th successful test of a Minuteman Stage III Change Verification Motor (CVM).

AEDC also developed a "too-inert-to-burn" concept, which allowed for cheaper and safer testing. The use of this concept became standard practice for Minuteman motors. The concept was successfully demonstrated during testing of a Minuteman Stage II motor in J-6 on April 6, 1995.

For the next 10 years, AEDC continued to support the Minuteman missile by conducting tests on the Stage II CVM and Minuteman Stage II and III motors.

Successful tests of the first of eight scheduled Minuteman motors were completed in January 2007 in test cell J-6. Since active Minuteman missile boosters are presently being replaced, this test will help to validate new production replacement program booster in the field today.

# PAC-3

## Patriot

*The Phased Array Tracking Intercept of Target (Patriot) missile is a long-range, high-altitude, all-weather system designed to defeat advanced threats, including aircraft, tactical ballistic missiles and cruise missiles. Combat proven during Operation Desert Storm, the Patriot can simultaneously engage multiple targets under the most severe electronic countermeasure conditions. The combat element of the Patriot missile system is the fire unit, which consists of a phased array radar set (RS) and engagement control station (ECS), an electric power plant, an antenna mast group, a communications relay group and up to eight launching stations.*



### Highlights of Development Testing at AEDC

- More than 180 hours of development testing
- Force and pressure tests in Tunnel A
- Heat-transfer studies in Tunnel B
- Lethality testing in 1999

The Patriot gained fame in the early 1990s during Operations Desert Storm and Desert Fox as it proved successful against the Scud missile. The Patriot defense system is a high-to-medium altitude, long-range air defense missile system that provides air defense for U. S. ground forces, installations and equipment. The system is designed to destroy enemy threats with a hit-to-kill, single-stage interceptor missile that can destroy enemy missiles within the earth's atmosphere before they reach their intended target. These capabilities cover threats from short- and medium-range tactical ballistic missiles, advanced cruise missiles and other air-breathing systems such as fixed- or rotary-wing aircraft.

Some 21 years before the Gulf War, the Patriot, then known as the SAM-D, began a testing program at the center that would continue through the turn of the 21st century.

The SAM-D missile underwent a total of 184 hours of testing in various AEDC tunnels during the three-year advanced development stage between 1969 and 1972. In early 1969, force and pressure tests were run in the von Kármán Gas Dynamics Facility's (VKF) Supersonic Wind Tunnel A, and heat-transfer studies were performed in the facility's Hypersonic Wind Tunnel B. Two years later, the 4-foot transonic wind tunnel (4T) was used to test the missile's control fin platform, and, in June 1972, the missile underwent force and pressure testing in the 16-foot supersonic wind tunnel (16S). At the same time, the missile's solid-propellant propulsion motor went through a series of test firings, and proof tests were performed on the launch technique to be used with the operational missile.

By the end of August 1974, all 10 control test vehicles had been successfully launched in the then-current series of test firings at the White Sands Missile Range in New Mexico.

In October of the same year, a series of 16 fully guided missiles was launched at White Sands in proof-of-principle tests for the Raytheon targeting missile guidance system.

### Characteristics

**Primary Function:** Surface-to-air missile  
**Contractor:** Lockheed Martin  
**Power Plant:** Single-stage solid propellant rocket motor with special altitude-control mechanism for in-flight maneuvering  
**Length:** 17 feet  
**Weight:** 700 pounds  
**Diameter:** 10 inches  
**Wingspan:** 1.64 feet  
**Range:** 12 miles  
**Maximum Speed:** Mach 5+  
**Ceiling:** 50,000 feet  
**Guidance Systems:** Inertial/Active wave radar terminal homing  
**Warheads:** Hit-to-kill and lethality enhancer 160.94 pounds HE blast/fragmentation with proximity fuze  
**Date Deployed:** May 1982  
**Inventory:** 6,217





**This scale model of the SAM-D missile was tested in the VKF to determine stability and control characteristics and force and moment data on the control fins. Surface pressure distributions were also measured to aid in developing body and fin design air loads and to determine local heating rates near and on the fins.**

On May 21, 1976, the SAM-D was renamed the Patriot Air Defense Missile System. The name was chosen to emphasize the air defense system's role as a strong defender of American freedom and national beliefs.

After flight tests in 1984 at White Sands, the Patriot missile became part of the Army's working inventory.

In the late 1980s, the Patriot returned once more to AEDC's wind tunnels, where center engineers examined the effects of high-speed flight through rain and ice on the guidance mechanism.

By 1999, AEDC was once again testing the Patriot – this time testing the lethality of a new missile configuration. The Patriot missile system underwent three configuration upgrades that provided enhanced critical defense capabilities. AEDC's Range G Hypervelocity Ballistic Facility tested the lethality of the upgraded version of the Patriot missile - the PAC-3, an integral part of the third configuration phase.

This testing was an important contribution to the overall PAC-3 Lethality Live Fire Test and Evaluation (LFT&E) Program and was required before the missile could proceed into production. It was an essential element to getting PAC-3 fielded for the nation's defense.

The AEDC tests were designed to investigate the missile's lethality characteristics against specified tactical ballistic missile targets. To meet launch requirements, the Range G team installed a special 4-inch-diameter barrel to create a 40-percent scale test range. The live-fire test also required impact on the target with the projectile flying at a specified angle of attack. To accomplish this, the team used an innovative gas-jet technique to increase pitch of the projectiles to the desired angles.

Range G's "soft launch" capability allowed the simulated PAC-3 missile to be designed and launched with the highest possible fidelity. Each projectile was loaded with up to 1,800 psi of argon gas, thus allowing engineers to develop a predictable thrust vector as the gas escaped through an opening on the side of the projectile nosetip. Release of the gas was initiated at launch by an inertia-activated valving system, and pitch amplitude at impact was controlled by variations in initial gas pressure and flight distance to target.

Using this design, the team conducted 14 data shots at velocities up to three kilometers per second with impact angles from 8 to 31 degrees.

The next year (2000), the new PAC-3 system successfully engaged and destroyed a cruise missile target during a flight test at White Sands Missile Range. The new PAC-3 system has enhanced radar, improved survivability and a launch-point determination capability that will increase its battlespace and range.

This was the second successful test of PAC-3 in one week. The July 25, 2000, issue of *Defense Daily* reported that on July 22, it destroyed another cruise missile target. The July 22 test marked the seventh successful flight test of PAC-3 and the fifth successful intercept.

In 2002, two Patriot interceptor systems annihilated their targets over White Sands Missile Range due in part to development tests conducted at AEDC.

In separate tests, PAC-3 and PAC-2 interceptors were fired against a simulated Scud missile and a drone aircraft, respectively.

The Patriot system includes the interceptor, an upgraded radar, communications gear and battle-management equipment. The PAC-3 is an upgrade to the Patriot system used in the Gulf War and relies on "hit-to-kill" technology to intercept and destroy its target. The PAC-3 test was the second of four operational tests following development tests.



**AEDC tested the PAC-3 "hit-to-kill" missile in 16S. A rapidly deployable system, it provides short-range defense, defends deployed troops and provides continuous missile defense coverage for rapidly maneuvering forces. The PAC-3 system was deployed to the Middle East as part of Operation Iraqi Freedom, where it successfully engaged several ballistic missiles.**

# ALCM

## Air-Launched Cruise Missiles

*The AGM-86B air-launched cruise missiles and AGM-86C/D conventional air-launched cruise missiles were developed to increase the effectiveness of B-52H bombers. In combination, they dilute an enemy's forces and complicate defense of its territory. The AGM-86B/C/D missiles are powered by a turbofan jet engine that propels it at sustained subsonic speeds. After launch, the missile's folded wings, tail surface and engine inlet deploy. The AGM-86B can fly complicated routes through use of a terrain contour-matching guidance system. The AGM-86C/D uses an onboard GPS coupled with its inertial navigation system to guide itself to the target with pinpoint accuracy.*

### Characteristics

**Primary Function:** Air-to-surface strategic missile

**Contractors:** Boeing

**Power Plant:** Williams Research F107-WR-10 turbofan engine

**Length:** 20 feet, 9 inches

**Weight:** 3,150 pounds

**Thrust:** 600 pounds

**Diameter:** 24.5 inches

**Range:** AGM-86B: 1,500-plus miles

**Maximum Speed:** About 550 mph (Mach 0.73)

**Guidance System:** Litton inertial navigation element with terrain contour-matching updates

**Warheads:** Nuclear capable

**Date Deployed:** December 1982

**Inventory:** Active force, 1,628



### Highlights of Development Testing at AEDC

- Engine testing on the missiles' power plant
- Wind tunnel tests prior to its first test flight

The small, 600-pound-thrust turbofan jet engine developed for the Air-Launched Cruise Missile (ALCM) completed Preliminary Flight Rating Tests (PFRT) in 1975.

Built by Williams Research Corp., the F107 engine weighs 130 pounds. Two of these engines were used in a six-week test program conducted in one of the 10 high-altitude test cells of AEDC's Engine Test Facility (ETF).

The engines were instrumented and mounted on a thrust stand as test conditions simulated the various altitude and Mach number conditions the engine would encounter during a mission. A total of 54 engine operating hours was logged during the program.

Testing included the evaluation of simulated air-launched starts; determination of compressor stall margins; power transients; simulation of a mission profile; engine performance both with and without power extraction required for engine or weapon system accessories; and both with and without distortion of inlet airflow designed to simulate the effect of flight maneuvers on the engine.

After the PFRT program was completed, two additional F107 flight engines were calibrated and shipped to Boeing, where they were installed in the 14-foot-long ALCM airframes. Another engine, installed in the cruise missile, was tested in AEDC's Propulsion Wind Tunnel's (PWT) 16-foot transonic wind tunnel (16T).

Earlier tests at AEDC had involved demonstrations of the F107's air-start capabilities using both standard JP-4 fuel and high-density, high-energy JP-9 fuel. Wind tunnel tests of a full-scale operating model of the Air Force's ALCM were completed in late February, clearing the way for the missile's successful first powered flight on March 5, 1976.

Satisfactory demonstrations of control surface deployment and midair starts of the missile's jet engine under simulated launch conditions were required before the actual flight test could be performed at White Sands Missile Range, New Mexico. Following completion of these requirements, the missile was dropped from a B-52 bomber at 15,000 feet above sea level and flew for 11 minutes.

During eight days of ALCM testing in 16T, seven control surface deployments and 11 air starts of the engine were accomplished at a variety



**AEDC personnel check a quick-opening door at the F107 turbofan engine's exhaust nozzle. The door was opened as air was supplied to the engine's inlet to simulate an in-flight start.**

of launch speeds and altitudes. More than 25 operating hours were accumulated on the engine during the test program.

Although this was the first AEDC test of the Williams Research F107 engine combined with the Boeing Aerospace Co. missile, tests of the engine alone had been performed under the ALCM program throughout the year. Through February, a total of 15 engines – including the one used in the first powered flight – had been tested. Calibration of the engines to be used in the remaining scheduled test flights was also accomplished at AEDC.

In 1976, Lt. Gen. James T. Stewart, then commander of Aeronautical Systems Division, wrote in a letter to AEDC's commander that the recent first flight of the ALCM marked the successful completion of a major milestone in the advanced development program.

*"Your organization," he wrote, "specifically the personnel of the Engine Test Facility and Propulsion Wind Tunnel, made a significant contribution to the hardware test and evaluation effort, which was a prerequisite for flight release.*

*"In particular, there are three distinct phases of testing performed by your organization which deserve special recognition. One is the accomplishment of all planned objectives for the Preliminary*

*Flight Rating Test in ETF. There were several critical test cell modifications which were completed on schedule and aided immeasurably in determining the altitude performance characteristics of this engine.*

*"Secondly, the calibration of flight engines for the missile test program has established a firm database for later missile flight performance analysis. The timely completion of this testing has enabled us to meet all contractual schedules.*

*"The third phase was the airframe/engine integration test conducted in PWT. The completion of all planned test*



**An ALCM was tested in 16T prior to its first flight. The full-scale weapon is shown installed in 16T in 1976.**

## Air-Launched Cruise Missiles



The General Dynamics ALCM is readied for testing in 16T in 1979.

*objectives ahead of schedule provided invaluable data to substantiate flight performance predictions and greatly enhanced our confidence in the attainability of the first flight goals. The fact that this effort was immediately preceded by two other system integration tests conducted under severe scheduling constraints speaks highly of the excellent resource management and technical competence of all personnel associated with this work.*

*“Please relay the sincere appreciation and congratulations of both myself and Col. MacIvor, ALCM program director, on a job well done. It would not have been possible without the professional expertise and ‘can do’ attitude demonstrated by the members of your organization. I look forward to your continued participation in development of the cruise missile.”*

In 1977, a new computer-controlled jet engine testing technique enhanced the effectiveness of testing jet engines in ETF’s altitude test cells. The technique was used for the first time in testing the Williams Research Corporation’s F107 jet engine, which powers the ALCM.

The system involves programming a computer to control the powerful air compressors, exhaust pumps, refrigeration and heating units of the ETF. The airflow supplied to one of the facility’s 10 high-altitude cells simulated the flight conditions the ALCM would encounter as it was released from a B-52 bomber above the Holloman Air Force Base (AFB) test range in New Mexico.

The temperature, velocity and quantity of the airflow, and the pressure around the engine’s tailpipe were

sequentially changed to duplicate the conditions the engine would encounter as it first dove to a very low altitude and then followed the mountains and valleys that make up the terrain in that area.

Two complete missions, from launch until impact, were simulated during one three-hour test period.

Throughout the “flights,” hundreds of instruments recorded engine operation: start sequence, fuel flow, temperatures, vibrations, fuel consumption, thrust and other aspects of operation.

The engine was controlled by a second computer programmed to change throttle settings to match the continuously changing simulated flight conditions.

By 1980, qualification tests of the ALCM’s Williams Research Corporation F107 turbofan engine had been undergoing tests in an AEDC high-altitude test cell for eight years.

During one particular test, the 140-pound engine, which generates 600 pounds of thrust, was tested for six consecutive work days at conditions simulating actual flight of the cruise missile.

Part of the testing required that the engine be run continuously for five hours at 20 degrees below zero Fahrenheit. In this instance, a liquid air injection system was used for the first time to furnish the engine with an ample supply of super-cold air.

In order to simulate actual ALCM missions, the engine was tested at temperatures from -65 to 150 degrees Fahrenheit at altitudes simulating flight from sea level to

35,000 feet. The engine was continuously run for five hours at -20 degrees Fahrenheit.

In 1982, the air intake of the ALCM was being tested under icing conditions.

The tests involved operating the missile's engine while it was installed in the aft section of a full-scale ALCM.

Test conditions in the 16-foot-diameter, 72-foot-long cell simulated flight through icing clouds at speeds from 300 to 600 mph at altitudes from 1,000 to 14,000 feet.

To simulate the icing cloud an array of 75 nozzles was used to spray a fine water mist into the airflow passing over the missile. The airflow and water droplets were chilled below the freezing point to create conditions the missile would encounter as it flew through icing clouds.

Motion picture and TV cameras were used to study ice buildup on the engine inlet as the engine was operated at various Mach numbers and altitudes. Other instrumentation attached to the engine monitored its operation, including degradation in thrust caused by ice buildup on the intake.

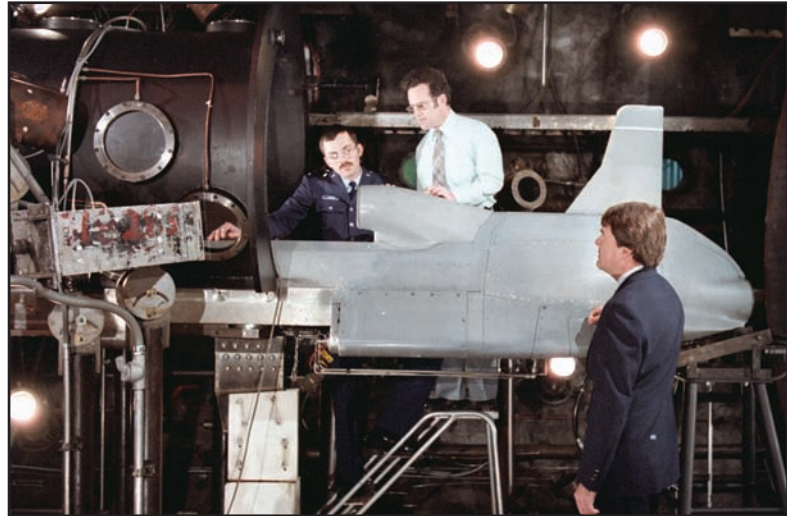
Test data are being used as the basis for programming the missile's speed and altitude as it passes through icing clouds, making adjustments that can enhance its ability to fly in severe icing environments. The effectiveness of an anti-icing device – an electric “lip heater” installed in the rim of the intake – was also evaluated during the test as a means to prevent ice buildup.

Improvements in controlling the temperature and flow rate of the water spray system provided new capabilities in more quickly establishing a uniform distribution of ice cloud water droplets in the test airflow.

The test required very precise metering of the water injected into the airstream. For example, a typical cloud was the equivalent of injecting one gallon of water into a 44-inch-diameter column of air eight miles long.

Uniform distribution of 20-micron-size droplets (slightly smaller than one thousandth of an inch in diameter) was produced in the high-speed airflow.

In previous tests the icing simulation system had been used to check the operation of large and small turbofan engines and a helicopter engine under a variety of icing conditions. A total of 52 separate test conditions were



**This full-scale aft portion of the ALCM, minus its horizontal stabilizers, was installed in 16T to test its engine air intake under simulated icing conditions. Chilled airflow containing ice cloud water droplets was supplied through ducting as the missile's engine was operated at conditions simulating various speeds and altitudes. Data checked the engine's performance including degradation in thrust caused by ice buildup on the intake.**



**As a preliminary to its successful first flight on March 5, 1976, a full-scale model of the ALCM was tested to verify the missile's operation under simulated launch conditions. Of principal interest in support of the flight program were the ability of the missile's aft control surfaces to deploy and its jet engines to start in midair. Additional tests were also conducted to examine control surface deployment, engine-inlet compatibility and low-temperature engine starting characteristics over a wide range of launch conditions and flight attitudes. The tests were conducted in 16T.**

successfully investigated during the three-week test program.

Also during 1982, AEDC used Computational Fluid Dynamics (CFD) to determine whether the conditions in the test cell realistically simulated actual flight conditions. Test cell conditions were demonstrated by CFD to be similar to actual flight conditions in which the cruise missile is designed to fly.

# BGM-109

## Tomahawk

*The Tomahawk is a long-range, subsonic cruise missile used for land attack warfare, launched from U.S. Navy surface ships and U.S. Navy and Royal Navy Submarines. Current Tomahawks are designed to fly at extremely low altitudes at high subsonic speeds and are piloted over an evasive route by several mission-tailored guidance systems.*

*The Tomahawk carries a nuclear or conventional payload. The conventional, land-attack, unitary variant carries a 1,000-pound-class warhead, whereas the submunitions dispenser variant carries 166 combined-effects bomblets.*



### Highlights of Development Testing at AEDC

- **Analysis provided for the continued improvement of the Tomahawk Cruise Missile Program**

Current Tomahawk cruise missiles are designed to fly at extremely low altitudes at high subsonic speeds and are piloted over an evasive route by several mission-tailored guidance systems.

The first operational use of the Tomahawk was in Operation Desert Storm in 1991 with great success. The missile has since been used successfully in several other conflicts.

In 1995, the governments of the U. S. and the U. K. signed a Foreign Military Sales Agreement for the British acquisition of 65 missiles, marking the first sale of the Tomahawk to a foreign country. After a November 1998 launch and live warhead test, the U.K. declared operational capability.

Some 11 years prior to the operational use of the Tomahawk in Operation Desert Storm, AEDC was heavily involved in its development testing. In July 17, 1980, the center was conducting tests to ensure the accuracy of data taken by an instrumented rocket flying in the upper atmosphere at supersonic speeds. Conducted in one of the center's aerospace chambers, the tests provided data needed for proper calibration of a probe, which measures the ion charge in the upper atmosphere. Such data are needed for communications and environmental purposes. Since the shock waves around the rocket can alter atmospheric samples taken by the probe, engineers must know temperature and air density changes in the airflow around the instrumentation. Once these changes have been determined, the probe can be calibrated to take accurate measurements.

In August 1989, AEDC engineers performed testing and analysis for the Navy for the continued improvement of the Tomahawk missile. Thus the Tomahawk was tested in Propulsion Development Test Cell J-1 in support of the Navy Cruise Missile Program.

As it can be launched from standard submarine torpedo tubes, the Tomahawk family of cruise missiles sees a broad range of uses with the U.S. fleet on both surface ships and submarines. The Tomahawk features a terrain-contour-matching navigation systems (TERCOM) that periodically compares the missile's actual position to the planned flight path and updates the inertial navigation system. The then-current propulsion unit for the Tomahawk (circa 1989) was a Williams F107-WR-400 turbofan engine that had been evaluated in the J-1 test cell in a prior test program during 1985. Drawing from the experience gained at

### Characteristics

**Primary Function:** Long-range subsonic cruise missile

**Contractor:** Raytheon

**Power Plant:** Block II/III TLAM-A, C & D – Williams International F107 cruise turbofan engine, ARC/CSD solid-fuel booster; Block IV TLAM-E – Williams International F415 cruise turbojet engine, ARC solid-fuel booster.

**Length:** 18 feet 3 inches

**Weight:** 2,900 pounds

**Diameter:** 20.4 inches

**Range:** Block II TLAM-A – 1350 nm; Block III TLAM-C – 900 nm; Block III TLAM-D – 700 nm; Block IV TLAM-E – 900 nm

**Maximum Speed:** 550 mph

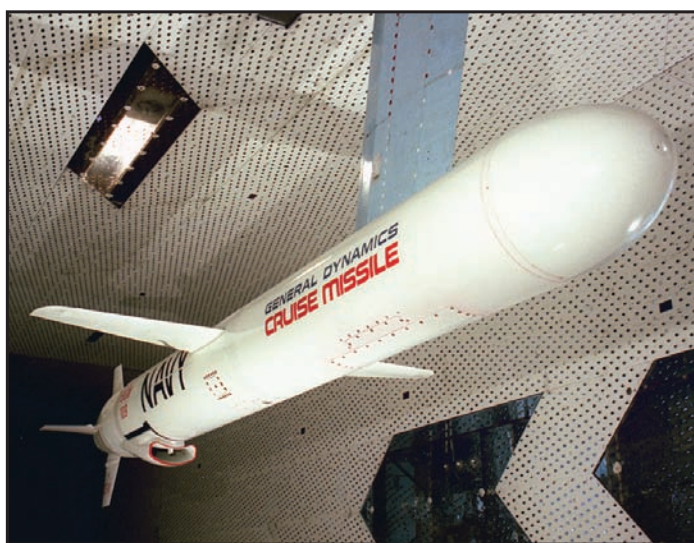
**Warheads:** (Warhead) Block II TLAM-N – W80 nuclear warhead; Block III TLAM-C and Block IV TLAM-E – 1,000-pound-class unitary warhead; Block III TLAM-D – conventional submunitions dispenser with combined-effect bomblets.

**Date Deployed:** Block II TLAM-A IOC – 1984; Block III – 1994; Block IV – 2004

**Inventory:** 4,170 missiles



A Tomahawk model is readied for testing at AEDC in 1985.



The Navy Tomahawk Cruise Missile used against Iraq during Operation Desert Storm was tested in 16T.

that time, AEDC supported the Tomahawk program with testing of a replacement turbofan engine, the Williams F107-WR-402, which enhanced performance of the existing F107-WR-400 engine.

The Navy Cruise Missile Program Office authorized Williams to begin development of the F107-WR-402 engine and perform comparison testing with the F107-WR-400 at the Naval Air Propulsion Center. As a result of that testing both Williams, the engine contractor, and General Dynamics, the airframe contractor, recommended that full-scale testing of the Tomahawk be conducted with both engine types at AEDC. An extremely aggressive schedule was required to prepare for and complete the Tomahawk test in the J-1 test cell within the required time. AEDC personnel worked 40 hours a week for five consecutive weeks in support of this test program, with only three hours lost due to equipment delays.

The testing required flight simulation of the General Dynamics full-scale model of the Tomahawk missile at

an altitude of 10,000 feet at Mach numbers ranging from 0.45 to 0.65. The desired flight conditions were simulated with the -20 degrees attained by injection of liquid air into the airstream.

Three major objectives of the J-1 testing were to (1) define the worst and best Tomahawk production inlets from a sampling of 18 inlets; (2) evaluate the effects of the worst and best inlets on the -400 and -402 engines; and (3) determine the effects of sideslip angle on the operation of the engine. The test procedure for these objectives required increasing the engine throttle every 30 seconds until a predetermined rate of engine surges was found.

Engine surges were generally noticed as flashes from the engine tailpipe. (A surge is a momentary reversal of the flow within the engine.) The engine surges were monitored by the J-1 data acquisition system at a sampling rate of 100 samples per second.

The successful completion of this testing provided the Navy with the information needed to support the planned flight testing and to assist in the production decision on the new Tomahawk propulsion system.

In 1997, AEDC again conducted performance verification testing on the F107-WR-402 engine, which was the then-current Tomahawk missile engine. By the time it was replaced, Williams International would have delivered more than 7,000 of these second-generation F107 cruise missile engines for Navy Tomahawk and Air Force Air-Launched Cruise Missiles.

During the summer of 2000, AEDC signed a contract with the Raytheon Company on behalf of the U.S. Navy for engine tests for a new Tactical Tomahawk (TACTOM) program to be performed in Propulsion Development Test Cell T-11. The testing, performed in 2002, confirmed that the TACTOM, the next generation of the Navy's Tomahawk long-range cruise missile system, was capable of completing its assigned mission on time and on target. The engine that would power the new Raytheon-built TACTOM missile was the Williams International F415-WR-402, a smaller version of the Taurus missile engine, which AEDC had tested in 2000. Testing and certification of the F415-WR-402 engine lasted for a year.

During 110 hours of testing in test cell T-11, the test team simulated hot- and cold-day conditions to evaluate the operability and performance of the F415 engine in different atmospheric climates. They evaluated smoke and exhaust emissions to establish how efficiently the engine burned fuel during a mission, and they conducted endurance studies to determine how far the missile could fly under the various conditions.



**The Williams International F415 engine, installed for testing in test cell T-11, powers the Navy's next generation Tomahawk cruise missile system, the Tactical Tomahawk.**

Mission endurance is critical to a long-range cruise missile system's success. The data obtained in the test cell T-11 gave the customer a clear understanding of how their engine would perform under different flight and mission conditions and confirmed that the engine (1) more than met its thrust and efficiency goals, and (2) the missile system could successfully reach its target. The Tactical Tomahawk test program also successfully demonstrated a new realm of cruise missile test capabilities in T-11.

For the tests, AEDC employees modified T-11, a former Navy test cell, to provide better data and more efficient operations. To support future cruise missile testing, they also added new test capabilities. T-11 employees installed universal engine installation interface panels for engine instrumentation, as well as support systems that allow quick installation of a wide range of small engines in the test cell. These cell modifications provided improved real-time mission simulations and data acquisition. The installation interface makes first-time installations faster and allows the customer to mate up to standard interface points, thus reducing their test costs. In most cases, an engine test entry can now be completed in less than one week.

The T-11 team also installed a new fuel temperature control capability that increased the fuel temperature range by 25 percent and resulted in a very stable system that can automatically maintain temperatures from -65 to 186 degrees Fahrenheit. An updated mission simulation control system ensured an accurate simulation of the entire cruise missile mission from start to finish. It automatically controlled the mission flight conditions and interfaced with

the engine control system to create a seamless integration of the engine with the facility that resulted in a realistic simulation of the actual missile mission.

New cameras installed in the engine's inlet also provided valuable information on how the engine performed in cold atmospheric conditions, and cameras in the exhaust flow allowed the customer to see how hot the engine became during the simulated mission. Since ice ingestion was a concern, the inlet cameras allowed the customer to ensure that there was no significant buildup before or during engine tests. The exhaust cameras provided information that has never been seen before as well as a visual representation of the overall turbine temperature profile.

The AEDC Applied Technology Department conducted emissions and smoke number measurements during the tests to determine the fuel-burn efficiency. The analyzed gas samples provided data on fuel combustion at simulated altitude conditions, and a new optical smoke meter developed by the department provided real-time transient smoke numbers during the simulated mission.

A later variant, the Tactical Tomahawk Block IV missile is a long-range, highly accurate, guided missile with the capability to deliver a unitary payload to a preplanned location. The Block IV program expands responsiveness and capabilities of the Tomahawk Weapon System with lower-cost airframe and electronic technologies. This new generation TACTOM is designed not only with a new airframe, but with new avionics architecture, new mission control software, new rocket motor assembly, and a new cruise engine.



# Peacekeeper

## Intercontinental Ballistic Missile

*The development of the Peacekeeper began with the intent of being a counterforce, hard-target weapon. It was to be aimed at hardened enemy missile silos with first-strike capability, which required accuracy, survivability, range and a flexibility not available in the Minuteman III. The Peacekeeper was much larger than the Minuteman, being more than 70 feet long (The Minuteman was 59.9 feet long.) and weighing 198,000 pounds (The Minuteman weighed 79,0442 pounds.). Under the 1993 START II treaty, the missiles were to be removed from the U.S. nuclear arsenal in 2005 and, despite the demise of START II, the last of the LGM-118A Peacekeeper ICBMs were decommissioned in September 2005.*

### Characteristics

**Primary Function:** ICBM  
**Contractor:** Boeing  
**Power Plant:** First three stages, solid-propellant; fourth stage, storable liquid  
**Length:** 71 feet  
**Weight:** 195,000 pounds, including reentry vehicles  
**Diameter:** 7 feet, 8 inches  
**Range:** Greater than 6,000 miles (5,217 nautical miles)  
**Maximum Speed:** Approximately 15,000 miles per hour at burnout (Mach 20 at sea level)  
**Ceiling:** 500 miles  
**Guidance System:** Inertial  
**Warheads:** 10 Avco MK 21 reentry vehicles  
**Date Deployed:** December 1986  
**Decommissioned:** September 2005



### Highlights of Development Testing at AEDC

- **Key role in providing the Air Force with critical test data for stages II, III and IV of the Peacekeeper since the developmental missile program was initiated**

The Peacekeeper Intercontinental Ballistic Missile (ICBM) was built as a replacement for the Minuteman, in order to keep place with anticipated future Soviet ICBM capabilities. It was intended to be a counterforce, hard-target weapon; a missile silo killer with inherent first-strike capability. The missile experiment (MX) was developed to improve survivability, range, accuracy, payload and target flexibility.

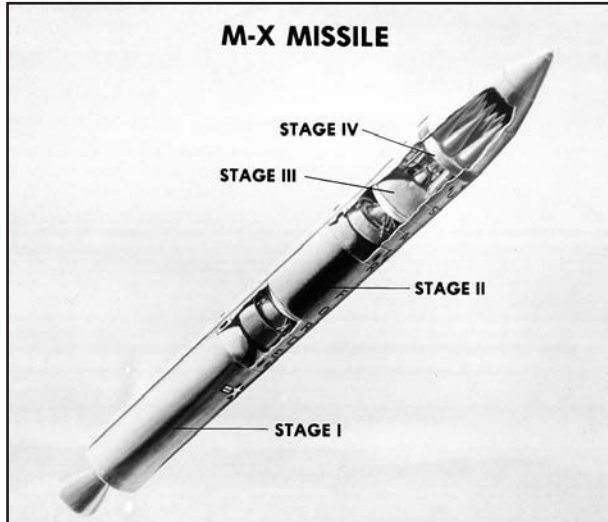
The development of the Peacekeeper missile system began in 1979, and in 1988, the new missile became fully operational.

Although the first test of a Peacekeeper propulsion system at AEDC was a Stage II solid rocket motor firing in the Engine Test Facility's (ETF) J-4 rocket motor test cell in December 1981, the center's work in preparing to support the high-priority missile system had begun several years earlier. In May 1980, the test sponsor, the Ballistic Missile Organization (BMO), allocated \$12 million to modify the J-4 test cell to accommodate the testing. Modifications included rebuilding the thrust stand, adding a thrust calibrator, rebuilding the diffuser and redesigning and rebuilding the steam ejector.

BMO also allocated \$1 million to modify the horizontal J-5 test cell for the Stage III and \$2.5 million to modify the J-3 test cell for the Stage IV. Another \$10 million was used to design, buy and install a new data acquisition system for J-4 and J-5 and an additional system for J-3.

AEDC has conducted 36 development motor firings, 12 full-scale flight proof tests, nine full-scale prequalification tests and 16 full-scale qualification tests in support of the Peacekeeper. All three stages have undergone production quality assurance (PQA) tests at AEDC.

Testing at simulated altitude conditions at AEDC revealed the need for the following design changes:



Altitude tests of the propulsion systems for the Peacekeeper Missile continued with successful Stage II rocket motor test firing. All upper stages have been tested at AEDC.

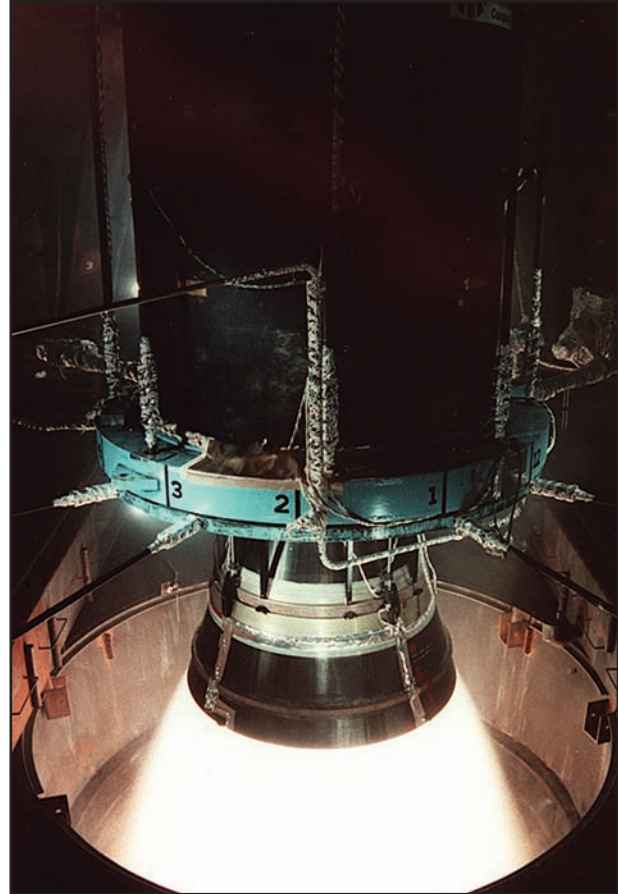
- Extendable Nozzle Exit Cone (ENEC) and nozzle
- Motor grain configuration for Stage II
- Stage III liner quality upgrade
- Nozzle extension hardware on Stage III

The purpose of the Peacekeeper testing at AEDC was simple – to see how the different stages would react at simulated altitude conditions. The reason for test firing the motors anywhere is to develop, verify and qualify the propulsion systems to be used on the intended weapon system. AEDC provided the high-altitude environment for such tests and produced highly accurate data in a timely and cost-effective fashion.

In the initial stages of the Peacekeeper motor testing, extremely detailed attention was paid to day-to-day operations because of the complexity of the systems. As time progressed, the systems became more familiar. The testing during the 1980s represented a critical phase in the development of the Peacekeeper missile system as well as a huge investment by BMO, an investment that totaled more than \$70 million since 1980.

AEDC engineers were involved in the Peacekeeper program almost from the beginning. “The Peacekeeper program has been a very satisfying one at AEDC because we got in on the ground floor,” one engineer said. “At the beginning of development testing of a rocket motor, you hold your breath just to see if the motor will hold together. Then after you see it’s going to survive, you become more interested in the performance. You then tighten the design spiral and polish the development. We went that route here. We participated in the whole life cycle of the development of the upper stage propulsion systems.

“Participating in both the Minuteman and Peacekeeper programs, it has been interesting to watch the evolution of the hardware. With each succeeding cycle, the materials



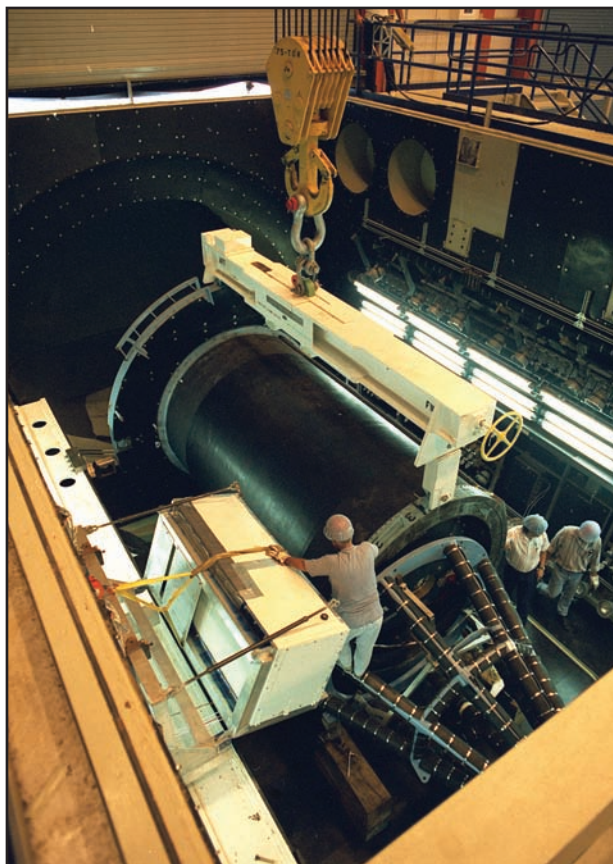
A Peacekeeper ICBM Stage II rocket motor was fired in the Rocket Development Test Cell J-4. AEDC test fired Peacekeeper Stage II and III rocket motors as part of the program’s qualification tests.

have gotten better. The research community has also learned more and become better, and as a result, the Peacekeeper should be more reliable than the Minuteman. We are on the cutting edge of rocket motor technology.”

Peacekeeper flight dynamics testing began in 1980 at AEDC and was conducted in Tunnels A, B and C. The Peacekeeper is a strategic missile capable of hypersonic and supersonic flight, and center engineers did basic testing of the system, conducting stability control and basic aerodynamic parameter testing to search for the optimum configuration. The testing covered the range from low supersonic to Mach 10.

Innovations that arose from these tests have now been developed and will be used in the future. For example, one such test involved a heating problem on the surface of the missile. From a certain distance, the Peacekeeper looks sleek. In reality, however, it has craters and bumps and channels all over it. Engineers were asked to determine the heating patterns around those bumps.

Normally, a 5-percent scale model would be put into the tunnel. However, since some of the bumps on the full-size missile might be as small as three inches, on a 5-percent



**The Peacekeeper Stage II ICBM rocket motor is prepared for the first validation motor firing in the J-6 rocket test cell.**

scale model they would be very small. The problem was how to work on something so small, especially since a full-scale model was simply too expensive. These engineers had to find another way. A technology program was set up to study ways of conducting this test. Larger scales of the model – even up to 1/10th scale – were put into the tunnel and tested, but these were still very small. The idea was then conceived to simulate the flow over the whole body of the missile using the sides of the tunnel as the missile, actually mounting bumps on the sides of the tunnel and flowing air over them. Although the results were not satisfactory at the time, the concept went on to be successfully used later, with different approaches.

Another question posed to the engineers at AEDC concerned the thermal material that protected the missile during launch and ascent. The project team went through the process of looking at different types of heat lamps to simulate the very high heat loads that the missile would have to endure during unusual circumstances. From this research came a concept called radiant augmentation of heating.

A Stage II/III separation test that did produce satisfactory results was run in the aerospace chamber 12V. The purpose of the test was to perform a staging maneuver using a 1/15th

scale staging mechanism, including the motor, at 300,000 feet in a zero gravity environment.

Under simulated zero gravity conditions, the motor was fired and measurements made. But engineers needed a means to measure the displacement of the two stages precisely. The result of their work was an interferometer, a way to use the wavelength of light, as a means of determining a distance. Using an interferometer with a helium-neon laser with a wavelength of .00005 inches mounted on each stage, engineers were able to measure the precise position of each stage during the actual maneuver.

By the end of the 1980s, AEDC had achieved significant milestones in the qualification testing of the PK Stages II, III and IV.

The last Peacekeeper Stage IV was tested in the Rocket Development Test Cell J-3 in 1986. The stage was evaluated through a series of recent AEDC tests for integrated stage performance, ordnance systems operation and vibration characteristics. Stage IV contains nine separate liquid-fueled rocket engines, which are cycled on and off approximately 2,600 times during its normal 17-minute mission duty cycle.

In 1988, AEDC successfully test fired the third Peacekeeper Stage III solid-propellant PQA rocket motor in Rocket Development Test Cell J-5. The program ensures that the motors function properly and according to rigid Air Force specifications by periodically test firing randomly selected motors in a simulated altitude environment while data are recorded.

The 22nd Peacekeeper Stage II rocket motor was tested in 1989 in test cell J-4 to ensure that the motor's performance would meet Air Force specifications. The motor was the fourth in the PQA test series.

The Peacekeeper Stage II motors are the largest solid propellant rocket motors ever test fired at AEDC. This motor was successfully test fired at a simulated altitude of 55,000 feet with approximately 50 channels of instrumentation used to collect motor performance data.

The PQA motors were preceded by 18 Peacekeeper Stage II simulated high-altitude test firings. These firings, which included five development series motors, four flight proof series motors, two prequalification motors and seven qualification motors. It was expected that an Aging and Surveillance (A&S) test program would also be conducted.

During the 1990s, AEDC continued to support the Peacekeeper program. In 1994, the post-boost vehicle (Stage IV) of the Peacekeeper was tested in J-3, marking the first test of the A&S test series. The objective of the program was to demonstrate conformance with motor performance requirements at different ages and to demonstrate aging capability of the motors. The post-boost vehicle provides all the attitude control during Stage III operation, burnout, and mechanical separation from the post-boost vehicle. The only Peacekeeper stage

## Peacekeeper

to burn liquid fuel, the Stage IV was equipped with a pressure-fed storable bipropellant system containing 1400 pounds of propellant, with one gimbaled main (axial) engine and eight attitude control engines used for steering the stage during reentry vehicle deployment. Conducted in altitude test cell J-3, the project involved hot fire testing of an A&S Peacekeeper Stage IV. For this particular test, the cell was pumped to an average internal pressure of 0.55 psia, simulating an altitude of 73,000 feet with a nominal test article temperature of 74 degrees Fahrenheit.

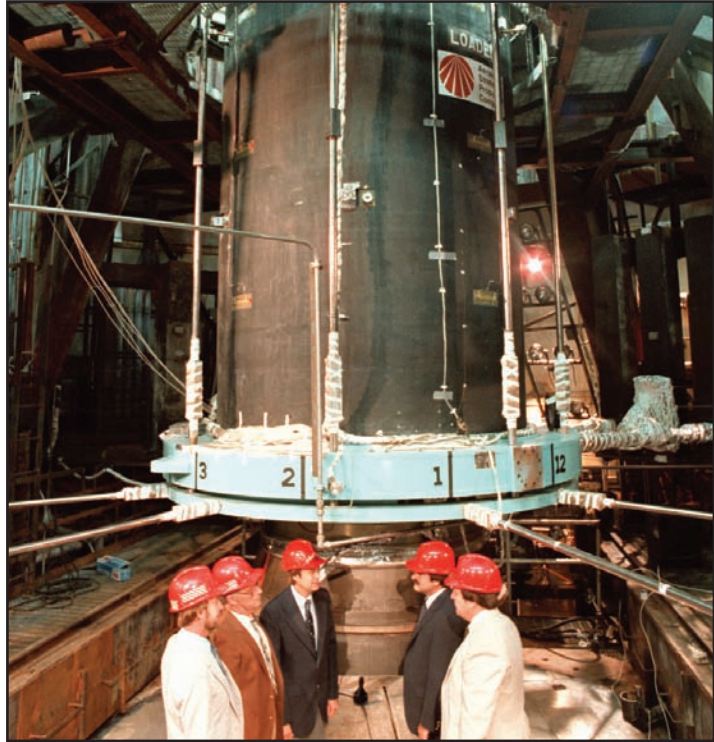
In 1995, a Peacekeeper Stage II A&S motor was successfully tested in test cell J-6 despite a bullet hole sustained by the motor while en route to Vandenberg Air Force Base (AFB), California.

In April 1995, the 60,000-pound rocket motor was shipped by rail to Vandenberg AFB for a missile flight test. Somewhere along the way, the motor's forward skirt was hit by a bullet. The damage was minor compared to the total loss that would have resulted if the bullet had pierced the section containing 55,000 pounds of flammable propellant. Because of normal rail noise, the event went unnoticed by train operators and remained undiscovered until engineers at Vandenberg AFB performed routine "as-received" inspections.

Personnel at the ICBM Program Office at Vandenberg AFB decided not to use the motor for flight testing. Instead, it was shipped to Hill AFB, Utah, for computed tomography inspections to determine the extent of the damage. Using the results from the tomography, Aerojet, the motor's manufacturer, conducted an independent stress analysis. Results of both examinations proved the motor was safe for static testing. ICBM office officials decided to use the motor for aging and surveillance testing at AEDC after manufacturer repairs were completed.

In June 1995, the motor finally arrived at AEDC, where base X-ray inspections reconfirmed the motor's safety. Preparations then began for an early December test. On Dec. 19, engineers in the center's J-6 facility completed last-minute requirements, and the countdown began. The motor was fired for 59 seconds at a simulated altitude of 98,000 feet with a thrust of 350,000 pounds. The test confirmed that all motor systems and subsystems still operated within specifications.

Most recently, in May 2008, a Peacekeeper Stage III A&S was tested in the J-6 test cell to determine the effect of age on the performance of the solid-rocket motor. This test marked the 91st firing of a large solid-fueled rocket motor under simulated high-altitude conditions in the J-6 test cell.



A Peacekeeper motor, installed in J-4, is examined by AEDC and customer personnel.



AEDC personnel closely monitor electronic test data in the control room during a test firing of a Peacekeeper Stage III solid-propellant rocket motor.

AEDC has previously tested 26 Peacekeeper Stage III motors for development, flight proof, qualification, production quality assurance and A&S programs.

The deactivation of the Peacekeeper fleet began in October 2002 after President George W. Bush set a plan in motion in 2001 to reduce the country's missile forces from 6,000 to between 1,700 and 2,200. Russian President Vladimir Putin agreed to follow a similar plan.



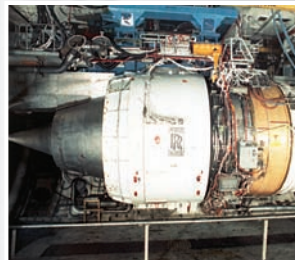
# Commercial Systems



Airbus A380



Boeing 787



Boeing 777



Boeing 767

# Commercial Systems Overview

During AEDC's first four decades, its customers were almost exclusively the U.S. military and NASA.

While commercial testing was available during these years, Department of Defense (DoD) regulations limited AEDC availability for commercial ventures. Two major changes in the early 1990s forced Arnold officials to rethink the role of AEDC. The first was increasing government budget pressures, and the second was global competition in the aerospace industry.

Decreasing budgets and reduction of new weapons programs made it increasingly difficult for AEDC to sustain the massive infrastructure and advanced technology so vital to developing next-generation weapons systems. With fierce global competition, U.S. industry found that maintaining in-house state-of-the-art test and evaluation capability is a burden that greatly impacts its competitive position.

Arnold officials realized that government and industry could both benefit from encouraging commercial use of the center. Industry could have access to the most advanced test and evaluation capability available in the world, offering a competitive advantage they could not afford to build and maintain themselves. AEDC could benefit from the commercial workload to sustain center capabilities for the benefit of the nation. These factors led to the establishment of partnerships between AEDC and commercial aerospace industries.

Expediting the venture into the commercial test arena, Congress passed a series of legislation between fiscal years 1994 and 1999 encouraging industry to use underutilized capabilities at DoD Major Range Test Facility Base (MRTFB) installations like AEDC. The law's purpose was to preserve MRTFB capabilities by keeping them in use; to reduce costs to all MRTFB customers by spreading sustainment costs over a broader revenue base; and to support the U.S. commercial competitiveness in the international market.

Additionally, the legislation reduced commercial testing prices, bringing them closer to government testing rates. The results of this new arrangement for commercial use of DoD test facilities was enhanced cooperation and collaboration in aerospace

technological development.

Commercial testing at AEDC is just one part of a larger national response to this national challenge. AEDC is now properly positioned to be a vital part of this nation's competitive strategy in the aerospace Research, Development, Test and Evaluation (RDT&E) marketplace. AEDC personnel can provide the expertise and resources necessary to support commercial customers. They possess world-class expertise in determining test feasibility, developing ground test requirements, conducting long-range test planning, scheduling and budgeting, designing, building and installing specially required test hardware and equipment, acquiring, processing and analyzing test data and correlating ground-to-flight data and performance.

Already, because of commercial testing, AEDC has been able to provide improved support to numerous defense and military efforts critical to the nation's defense. AEDC has maintained its unique capabilities and expertise in the field of aerospace ground testing.

There are two indirect benefits to the nation: (1) technology transfer between the commercial and DoD sector, and (2) direct use by DoD of commercial products. Additionally, critical DoD test and evaluation skills can be retained by conducting commercial testing during down periods of military testing requirements.

Technology transfer itself manifests both in the form of knowledge of test and evaluation methodology and in the form of investments in specialized equipment furnished to AEDC.



# Commercial Systems Timeline

## The 1950s

## The 1960s

## The 1970s

CF6-50

## The 1980s

## The 1990s



P&W 4084

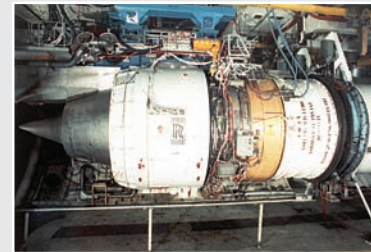
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Boeing 747

Boeing 767  
Trent 800

Boeing 777



Trent 800



Boeing 747

P&W 4090

Airbus A300-B2

P&W 4098



Trent 900

## The 2000s

Boeing 747

Airbus A380

Trent 900



Trent 1000

Trent 1000

GP7200

PW6000



GP7200

# Boeing 767

*The Boeing 767 is a wide-body jet introduced around the same time as the 757 in 1981. The Boeing 767 family includes three passenger models – the 767-200ER, 767-300ER and 767-400ER – and a freighter, which is based on the 767-300ER fuselage. Since the first 767 entered service, the planes have flown more than 7.7 million flights.*

## Characteristics

**Primary Function:** Wide-body jet

**Contractor:** Boeing

**Power Plant:** Two high-bypass turbofans, either GE CF6-80A (early 767-200 and 767-300 non-ER versions) or GE CF6-80C2 or Pratt & Whitney PW4062; a very limited number use the Rolls-Royce RB211  
**Thrust:** GE CF6-80A (65,000 pounds each); PW4062 (63,000 pounds each); Rolls-Royce RB211 (60,000 each)  
**Wingspan:** (767-200, 767-200ER, 767-300, 767-300ER, 767-300F) 156 feet, 1 inches; (767-400ER) 170 feet 4 inches

**Length:** (767-200, 767-200ER) 159 feet 2 inches; (767-300, 767-300ER, 767-300F) 180 feet, 3 inches; (767-400ER) 201 feet, 4 inches

**Height:** 55.4 feet

**Maximum Speed:** Mach 0.8

**Maximum Takeoff Weight:** 315,000 pounds to 450,000 pounds depending on model

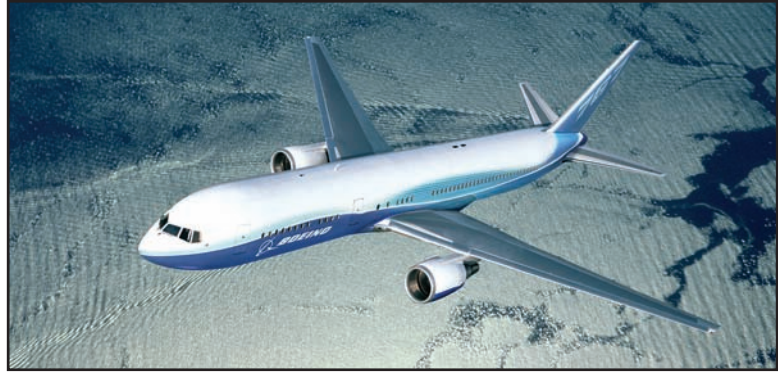
**Ceiling:** Varies

**Range:** 5,200 nm to 5,650 nm

**Crew:** Two

**Date Deployed:** Sept. 26, 1981

**Inventory:** 942



## Highlights of Development Testing at AEDC

- AEDC tests validated aerodynamic characteristics of the 767

In the summer of 1994, AEDC began testing on the first in a series of Boeing large commercial jets at AEDC. A model of the 767 was tested in 16T. The tests validated aerodynamic characteristics of the 767. The data obtained from AEDC were used to compare to data from tests conducted on the model in Boeing's wind tunnels, as well as in NASA and Russian wind tunnels.

Six years later, Boeing and AEDC entered into a three-year agreement for the center to conduct wind tunnel testing on several Boeing projects. The potential value of the workload for the various programs was estimated at \$30 million per year.

AEDC's 16T wind tunnel was used in 2001 to evaluate new engine designs for the Boeing Longer-Range 767-400ER airplane. The test was used to increase the operating range of the existing 767-400ER, making the engines more powerful, handling 72,000 pounds of thrust.

A 4.6-percent scale model was used with different mounting configurations to access the airplane's high-speed drag, handling characteristics and loads determination for a larger engine installation.



A model of Boeing's 767 commercial jet undergoes testing in 16T.



# Boeing 777

*The Boeing 777, a long-range, wide-body twin engine airliner, can carry between 278 and 550 passengers and has a range from 5,210 to 9,420 nautical miles. Since the first 777 entered service on June 7, 1995, 777s have flown more than two million flights. On May 30, 1995, the 777 became the first airplane in aviation history to earn FAA approval to fly extended-range, twin-engine operations (ETOPS) at entry into service. The 777 underwent the most extensive flight-test program ever conducted on a commercial jetliner.*

## Characteristics

**Primary Function:** long-range, wide-body, twin-engine airliner

**Contractor:** Boeing

**Power Plant:** (777-200) two, P&W 4077, two, RR 877, two, GE 90-77B; (777-200ER) two, P&W 4090, two, RR 895, two, GE 90-94B; (777-200LR, 777-200F) two, GE 90-110B; (777-300) two, P&W 4098, 2 X RR 892, two, GE 90-94B; (777-300ER) two, GE-90-115B

**Wing Span:** Depending on model, 199 feet, 11 inches to 212 feet, 7 inches

**Length:** Depending on model, 209 feet, 1 inch to 242 feet, 4 inches

**Height:** 60 feet 9 inches

**Maximum Speed:** Mach 0.84

**Maximum Takeoff Weight:**

Depending on model, 545,000 pounds to 775,000 pounds

**Ceiling:** 43,100 feet

**Range:** (777-200) 11,103.87 miles; (777-200ER) 16,474.56 miles; (777-200LR) 20,076.50 miles; (777-200F) 10,431.82 miles; (777-300) 12,691.95 miles; (777-300ER) 16,794.48 miles

**Crew:** Two

**Date Deployed:** June 12, 1994

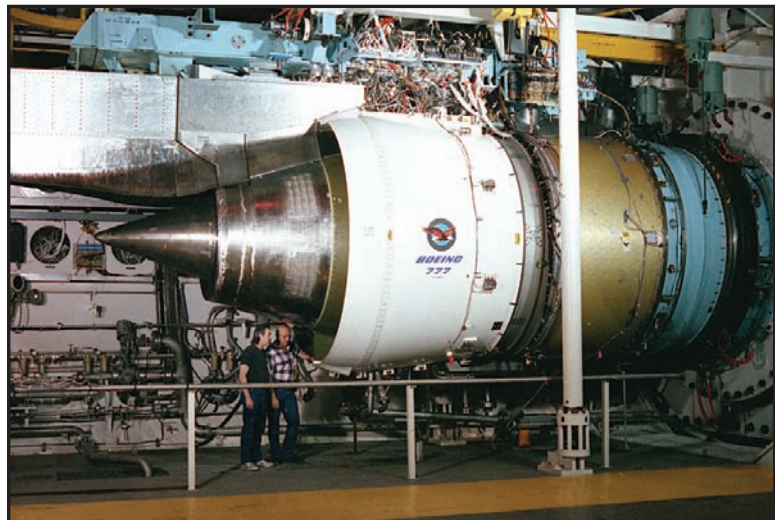
**Inventory:** 708 as of 2008



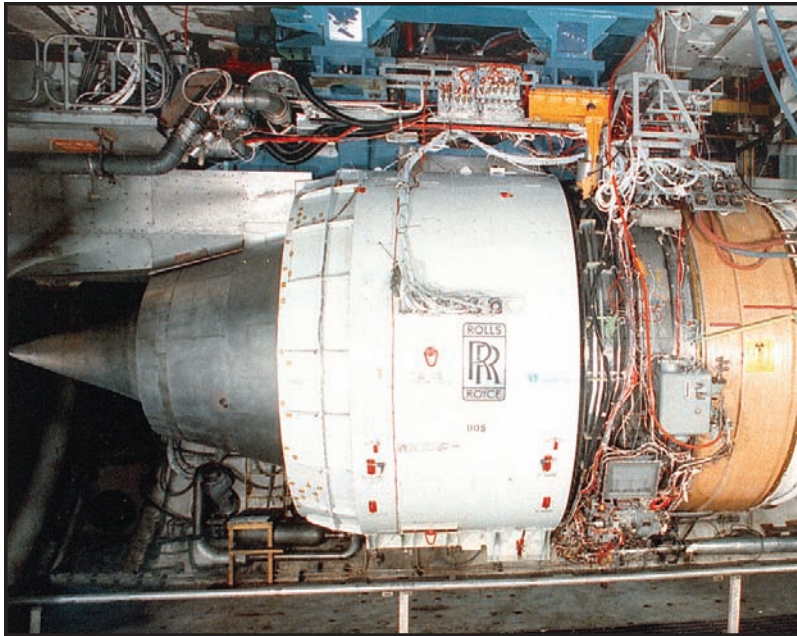
## Highlights of Development Testing at AEDC

- Turbine engine tests played a major role in ensuring Federal Aviation Authority (FAA) certification for the Pratt & Whitney (P&W) and Rolls-Royce engines
- Component testing provided simulation of multiple flight environments without the equipment and personnel risk associated with flight testing, saving time and money
- The engines that power the Boeing 777 and the airframe of the 777 successfully met the FAA reliability testing and validation requirements and certification criteria

On June 12, 1994, the Boeing 777 underwent its first test flight in Everett, Washington. Before the three hour and 48 minute test, the Pratt & Whitney (P&W) PW4084 had already logged more than 560 hours of simulated flight testing at AEDC. In fact, all of the Federal Aviation Authority (FAA) altitude certification for the PW 4084 engine as completed at the center.



P&W's PW4000 growth engine, designated the PW4084, was the second in a series of engines to undergo development and certification testing at AEDC.



Above, John E. Cashman, Boeing's chief pilot for the company's 777, "tweaks" the throttle during a test of P&W's 4084 engine at AEDC. Left, the Rolls-Royce Trent 800 engine powers some of the Boeing 777 commercial airliners. Tests at AEDC helped support Rolls-Royce's goal of achieving FAA certification.

Since the early 1990s, AEDC has supported development testing of P&W family of PW4000 commercial aircraft engines. The multi-million-dollar program provided multiple tests, involving about 100 hours each, of the new PW4000 growth engine in AEDC's Aeropropulsion Systems Test Facility (ASTF).

United Airlines, the launch customer for the Boeing 777 aircraft, selected the PW4073 model for its power plant. Additional growth models of the PW4000 engine provided the higher thrust levels required by new generation transport aircraft.

Commercial engine testing of the PW4000 growth engines at AEDC marked the beginning of a new era of partnerships between government and industry designed to keep the U.S. on the leading edge of the aerospace industry. The Air Force shared the information gathered from the test phase and joined with P&W expertise in applying Total Quality/Design of Experiment methodologies to the design and execution of the test program.

The P&W PW4084 commercial engine arrived at the center in September 1992 and was the first in a series of high-thrust PW4000 growth engines to undergo development testing at AEDC.

AEDC successfully completed simulated altitude testing on the PW4084, having demonstrated 90,000 pounds of thrust in January 1993. Testing of the PW4084 continued through 1993 and 1994. Test objectives included obtaining engine performance information during steady-state operation and engine operability during transient operation.

Additionally, during 1993, AEDC began planning development testing at the center of the Rolls-Royce Trent 800 high bypass turbofan engine.

A competing power plant for the Boeing 777, the Trent 800 is an 80,000-pound-thrust-class engine with a fan diameter of over nine feet.

Tests performed on the two engines sought to satisfy a number of objectives. Those included proving that the turbine engine was whirl-flutter free throughout the Boeing 777 flight envelope; that turbine operation was stable throughout the flight envelope; that the governor maintains speed control capability throughout the envelope and that the system performance was acceptable at minimum airspeed.

The test was divided into two halves that focused first on high-speed operation, from Mach 0.6 to Mach 0.944, and then on both high-speed and low-speed deployments.

Deployment tests were performed at various airspeed and altitude combinations, including Mach 0.15 at sea level and Mach 0.94 at 43,000 feet, which helped prove that the system would perform at any point in the aircraft flight envelope.

AEDC's role in the testing of the turbine was primarily to produce flight conditions and acquire on-line test data.

Representatives from Boeing and P&W were on hand at a Sept. 10, 1993, test to observe the PW4084 engine. The test was particularly important to ensure that when the engine is flight tested the data from the testing done at AEDC are representative of the actual flight test on the 777 test aircraft. Several Boeing pilots witnessed the first series of FAA certification altitude operability testing at AEDC.

The FAA announced in April 1994 that it certified an AEDC-tested P&W engine for use in the Boeing 777 flight tests.

In June 1995, the first commercial flight of the Boeing 777 took place from London to Washington, D.C.

# Boeing 747

*The Boeing 747 is among the most recognizable jet airliners. First flown commercially in 1970, it held its size record for more than 35 years until surpassed by the Airbus A380. There are five variants of the 747. The 747-100, the original, was launched in 1966, followed by the 747-200 in 1968, the 747-300 in 1980, the 747-400 in 1985, and the last, the 747-8 in 2005.*

## Characteristics

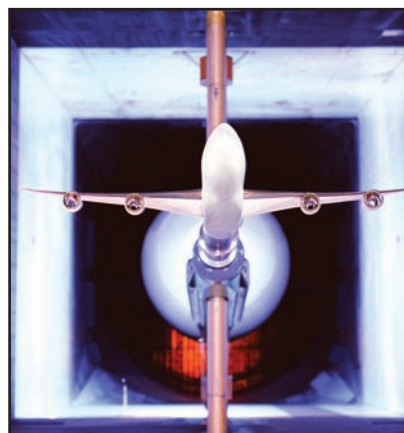
**Primary Function:** Jet airliner  
**Contractor:** Boeing  
**Power Plant:** (747-100) P&W JT9D-7A, GE CF6-45A2, RR RB211-524B2; (747-200B) P&W JT9D-7R4G2, GE CF6-50E2, RR RB211-525D4; (747-300) P&W JT9D-7R4G2, GE CF6-80C2B1, RB211-524D4; (747-400) P&W 4062, GE CF6-80C2B5F, RR RB211-524H; (747-400ERF) P&W 4062, GE CF6-80C2B5F; (747-81) GENx-2B67  
**Thrust:** 46,500-63,000 pounds  
**Wing Span:** 195 feet, 8 inches to 224 feet 9 inches, depending on model  
**Length:** 231 feet, 10 inches  
**Height:** 63 feet 5 inches  
**Maximum Speed:** Mach 0.89 to Mach 0.92  
**Maximum Takeoff Weight:** 735,000 pounds to 970,000 pounds  
**Ceiling:** 41,000 feet  
**Range:** (747-100) 9,800 km (5,300 nm); (747-200B) 12,700 km (6,850 nm); (747-300) 12,400 km (6,700 nm); (747-400) 13,450 km (7,260 nm); (747-400ERF) 9,200 km (4,970 nm); (747-8I) 14,815 km (8,000 nm)  
**Crew:** Three; (747-400, 747-400ERF, 747-81) Two  
**Date Deployed:** February 9, 1969  
**Inventory:** 1,402



## Highlights of Development Testing at AEDC

- Testing of new configurations of the aircraft during its development
- Engine, wings and wingtip and body testing

AEDC supported testing of the Boeing 747X in March 2001, conducting testing on new engines, wings and wingtips and longer body length. The program used a 3-percent scale Boeing aircraft model in the center's 16T wind tunnel to test configurations for the proposed aircraft. The tests allowed Boeing to raise the bar as far as testing excellence is concerned, allowing tests of the performance, stability and controls and aerodynamic loads during the same wind tunnel test and using the same model.



**A scale model of Boeing 747 derivative undergoes aerodynamic testing in 16T.**

Then a possible competitor with the Airbus A380 aircraft, the Boeing 747X transport would have been longer than the 747-400 aircraft with increased payload capacity. Other features include greater range, greater passenger capacity, faster speed and less takeoff noise than other 747 designs.

There are five variants of the 747, launched on five separate occasions. The 747-100 was the original and was launched in 1966. The 747-200 was the second model and followed soon after with an order in 1968. The 747-300 was launched in 1980. The 747-400 was launched in 1985, and the last, the 747-8, was launched in 2005. Although there are a total of five models, numerous versions of each type have been produced. Many of these variants were in production at the same time, especially in the 1980s. Air Force One, which transports the U.S. President, is a 747.

The 747-400, the only series currently in production, flies at high-subsonic speeds of Mach 0.85 (567 mph) and features intercontinental range.

# Boeing 787

*The Boeing 787 Dreamliner is a mid-sized, wide-body, twin engine passenger airliner under development and scheduled to enter service in 2009. It will carry between 210 and 330 passengers, depending on the seating configuration and will be more fuel-efficient than comparable earlier airliners. Boeing has selected two engine types – the General Electric (GE) GENx and Rolls-Royce Trent 1000 – to power the 787. For the first time in commercial aviation, both engine types will have a standard interface with the aircraft, allowing any 787 to be fitted with either a GE or Rolls-Royce engine at any time. Engine interchangeability will make the 787 a more flexible asset to airlines.*

## Characteristics

**Primary Function:** Mid-sized wide body, twin-engine passenger airliner  
**Contractor:** Boeing  
**Power Plant:** Two GE GENx or Rolls-Royce Trent 1000  
**Thrust:** 55,000 to 70,000 pounds  
**Wingspan:** (787-3) 170 feet, (787-8, 787-9) 197 feet 3 inches  
**Length:** (787-3, 787-8) 186 feet 1 inch, (787-9) 206 feet  
**Height:** 55 feet 6 inches  
**Maximum Speed:** Mach .85  
**Maximum Takeoff Weight:** (787-3) 360,000 pounds, (787-8) 480,000 pounds, (787-9) 540,000 pounds  
**Ceiling:** 43,000 feet  
**Range:** (787-3) 6,500 km, (787-8) 15,700 km, (787-9) 16,300 km  
**Crew:** Two  
**Date Deployed:** Test flight scheduled for 2009  
**Inventory:** 0



## Highlights of Development Testing at AEDC

- Trent 1000 tested for more than 65 hours in C-2
- Icing condition testing
- Full flight envelope testing

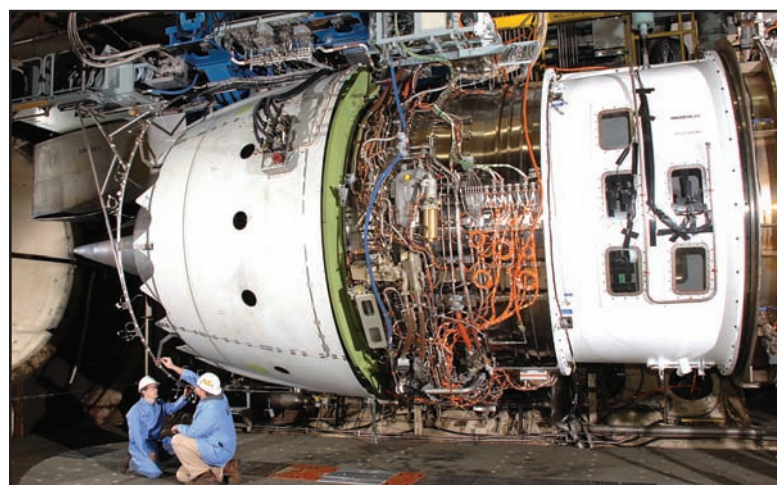
When the Boeing 787 made its maiden flight in 2008, it was powered by engines tested at AEDC.

Rolls-Royce reached a major milestone upon the completion of altitude testing on the Trent 1000 high-bypass turbofan engine in test cell C-2.

Data from the test paved the way for the first flight test of the Trent 1000 when one of the production engines was fitted to a Rolls-Royce owned Boeing 747 flying test bed aircraft located at Waco, Texas.

The test objectives included steady-state performance, engine operability and air starts, but the primary purpose of this project was to subject the engine to icing conditions at altitude for Federal Flight Administration (FAA) compliance certification. Icing certification testing at simulated altitude conditions is a capability unique to AEDC, especially for high airflow engines like the Trent 1000.

The Trent 1000 is the fifth version of the Trent to be developed since the engine family entered service 10 years ago. A single version of the Trent 1000 will be capable of powering all variants of the Boeing 787.



Test engineers inspect the Rolls-Royce Trent 1000 engine prior to testing. The windows on the inlet are used to observe ice build-up on the fan and spinner.

# Airbus A380

*The Airbus A380 is a double-deck, four-engine airliner manufactured by Airbus S.A.S. It first flew on April 27, 2005, from Toulouse, France. The A380's upper deck extends along the entire length of the fuselage. This allows for a spacious cabin with 50 percent more floor space than the next largest airliner, providing seating for 555 people in standard three-class configuration or up to 853 people in full economy class configuration. When the aircraft entered into service in late 2007, it was the world's largest commercial passenger jet. Either the Rolls-Royce Trent 900 or Engine Alliance GP7200 turbofans may power the A380.*



## Highlights of Development Testing at AEDC

- Tested Engine Alliance (EA) GP7200
- Tested Rolls-Royce Trent 900
- Testing led to FAA and EAA certification

The engines for the Airbus Industries A380 passenger aircraft were tested extensively at AEDC. Both the General Electric (GE)-Pratt & Whitney (P&W) Engine Alliance (EA) GP7200 and the Rolls-Royce Trent 900, which are offered to customers to power the aircraft, were tested in AEDC's large jet engine altitude simulation test facility to qualify the engines for flight on the new aircraft.

AEDC's Aeropropulsion Systems Test Facility (ASTF) is the only test facility in the world that can test very large, high-thrust engines in full simulated flight conditions.

Testing began on the Rolls-Royce Trent 900 engine in 2004. Following 97 hours of engine start and performance testing, AEDC engineers began a series of development tests to demonstrate safe engine operability during acceleration, deceleration and stall margin. Crews in the ASTF test cell C-2 tested the engine at simulated altitude conditions up to 43,000 feet and speeds up to Mach 0.98.

A month later, the EA GP7200 engine, which was developed for the Airbus A380, arrived at AEDC for altitude testing. The tests were conducted in test cell C-2.

The GP7200, built on the technological advancements of the GE90 and the PW4000, is one of eight engines the Engine Alliance plans to use to accumulate more than 20,000 endurance cycles and 7,000 hours of test facility operations before its entry into service. Achieving that number of cycle and operational hours exceeded standards set by previous engines qualified for the Extended Twin-Engine Operations (ETOPS).

The GP7200 engine was selected for more than 60 percent of the Airbus A380 aircraft orders with engines specified to date.

In June 2004, AEDC provided flight certification data for the Rolls-Royce Trent 900 engine. The test, which once again was conducted in ASTF, validated the engine's performance and icing characteristics and completed the entire range of required Federal Aviation Association (FAA) and European Joint Aviation Authorities (JAA) performance criteria.

The purpose of the icing test was to demonstrate that the engine could

## Characteristics

**Primary Function:** Double deck, four-engine airliner

**Contractor:** Airbus Industries

**Power Plant:** (A-380-800) 4 x GP7270 or Trent 970; (A-380F) 4 x GP7277 or Trent 977

**Thrust:** (A380-800) Four 70,000-pound, initially derated to 68,000-pound, later growing to 84,000-pound-thrust Rolls-Royce Trent 900 or 81,500-pound thrust Engine Alliance GP-7200 turbofans

**Wing Span:** 261 feet, 10 inches

**Length:** 239 feet, 6 inches

**Height:** 79 feet, 1 inch

**Maximum Speed:** Mach 0.89

**Maximum Takeoff Weight:** (A-380-800) 1,235,000 pounds; (A-380F) 1,300,000 pounds

**Ceiling:** 43,000 feet

**Range:** (A-380-800) 9,206.24 miles; (A-380F) 6,444.36 miles

**Crew:** Two

**Date Deployed:** April 27, 2005

**Inventory:** 26



Left, a Rolls-Royce fitter checks instrumentation on the Trent 900 engine for testing in C-2. The engine, selected as a power plant for the Airbus A380 passenger aircraft, underwent engine operability, performance and icing tests. Above, Robert Saia, an executive vice president of the GE-P&W EA, speaks to assembled AEDC craftsmen and management personnel in ASTF test cell C-2 with the first EA GP7200 engine as his backdrop.

successfully shed ice that built up during flight and could be resistant to or tolerate any damage from the icing conditions. The icing tests were also JAA performance certification criteria.

The icing test consisted of injecting an extremely fine water mist upstream of the engine to create simulated specific types of clouds such as freezing fog that the engine might fly through or encounter when the aircraft is descending for a landing or waiting for takeoff in very cold, foggy conditions.

Test crews documented ice formation on the engine inlet as well as the shedding of the ice. They visually inspected after each cloud test using high-speed cameras. These conditions simulated actual icing conditions that the engine might experience while flying at altitudes up to 25,000 feet.

In the fall of 2004, personnel at AEDC completed performance and operability testing on the first EA GP7200 engine being developed for the Airbus A380 passenger aircraft. During the three-month test program at AEDC, the GP7200 engine underwent 83 hours of simulated high-altitude testing at various inlet temperature conditions.

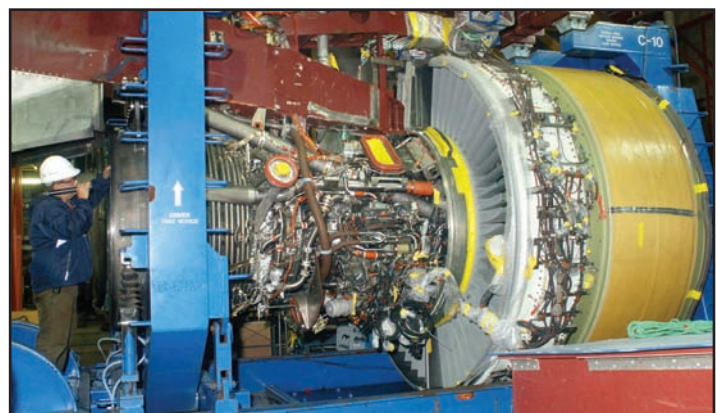
The goal of the initial test on the GP7200 was to determine how the engine compressor and fan performed in realistic flight conditions and to assess engine operation limits.

The engine was instrumented with more than 4,200 channels to gather information during the test, as compared to around 2,000 channels on the P&W PW4000 engine series.

The data will provide information that will allow the EA to optimize various engine designs.

AEDC personnel also conducted a series of icing tests on the GP7200. The prime objective of this particular test series was to get FAA certification for the engine to fly through clouds in different altitude conditions. The conditions vary from a ground cloud, such as fog, up to 20,000 feet, where freezing conditions can present icing hazards. The purpose of the test is to document how ice builds up on the engine.

After the simulated cloud is completed, the engine is accelerated to shed the built-up ice. Then the engine is shut down and inspected to make sure that no damage was caused by the ice. The first full passenger-carrying flight for the Airbus A380 took place in September 2006. The aircraft flew from Toulouse, France with 474 Airbus employees on board.



An AEDC quality officer performs an “as received” inspection of an EA GP7200 engine, a power plant for the A380 Airbus commercial airliner, before it underwent icing tests in the C-2 test cell.

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**F-117 Nighthawk (60)** – AEDC news releases: 90-096; 96-084; 96-168; 96-178; 97-135; 98-222; 2000-358; 2001-023; 2001-094; 2002-206; 2003-082; 2003-153; *AEDC plays role in support of Desert Fox; AEDC tests stealth fighter's weapons*. Photo and caption: AEDC PHOTO #94-118311. Spring/Summer 1990 Test Highlights. Lockheed Martin fact sheet.

**F-14 Tomcat (69)** – AEDC news releases: 88-152; 90-071; 92-046; 98-093; 2000-129; 2006-186; AEDC plays role in support of Desert Fox. Photo and caption: AEDC PHOTO # 89-60828. *High Mach* issue: April 1969; May 1969; July 1968; September 1988; April 1990; April/May 1991. July 28, 2006.

**F-15 Eagle (45)** – AEDC news releases: 73-28; 73-37; 73-50; 74-120; 74-124; 74-141; 74-174; 74-83; 74-98; 75-1; 75-128; 75-95; 76-40; 76-55; 77-212; 77-72; 78-130; 78-148; 79-61; 86-055; 86-145; 88-074; 90-101; 91-108; 91-187; 91-242; 91-260; 92-034; 93-142; 93-225; 94-051; 94-204; 96-093; 96-138; 96-191; 97-062; 98-137; 99-061; 2000-311; 2000-345; 2000-346; 2000-349; 2001-093; 2001-177; 2001-262; 2001-270; 2002-307; 2003-029; 2003-154; 2003-169; 2004-005; 2004-063; 2004-190; 2005-186; *Ripple Launch Computational Capability; AEDC tests aim to make F-15E fighter more versatile; F-15E Ballistic Accuracy Improvement; Pratt & Whitney F100 completes component improvement tests in T-1; The AEDC and Pratt and Whitney Alliance; Modeling and simulation at AEDC*. *High Mach* issue: January 1979; December 1980; February 1981; May 1985; June 1985; October 1985; April 1986; May 1986; August 1986; July 1987; August 1987; September 1987; November 1987; May 1988; June 1988; January 1989; July/August 1989; September 1989; November 1989; December 1989. Spring/Summer 1989 Test Highlights; Fall/Winter 1989 Test Highlights; Spring/Summer 1990 Test Highlights; Winter/Spring 1991 Test Highlights; Summer 1992 Test Highlights.

**F-16 Fighting Falcon (50)** – AEDC news releases: 74-125; 75-10; 75-137; 75-138; 76-5; 76-12; 76-208; 76-220; 77-20; 77-180; 77-181; 77-210; 78-24; 78-16; 78-93; 78-177; 79-19; 79-66; 82-067; 82-130; 86-055; 86-137; 86-147; 87-004; 87-032; 87-066; 87-076B; 87-128; 87-150; 88-078; 88-110; 89-042; 89-207; 90-067; 90-147; 92-043; 92-046; 92-071; 93-022; 93-089; 93-186; 94-049; 94-051; 94-073; 95-118; 95-141; 96-094; 97-862; 98-076; 98-100; 99-027; 99-169; 99-186; 99-269; 99-281; 2000-044; 2000-076; 2000-167; 2000-260; 2000-349; 2001-002; 2001-005; 2001-023; 2001-092; 2001-095; 2001-261; 2001-270; 2001-390; 2002-107; 2002-137; 2002-193; 2002-244; 2003-163; 2003-284; 2004-039; 2004-123; 2004-190; 2005-362; 2005-390; 2005-392; 2005-395; 2005-419; *AEDC plays role in support of Desert Fox; F-16 Fighting Falcon celebrates 25<sup>th</sup> anniversary of first flight; General Electric's enhanced fighter engine begins testing in J-2; Wind tunnel tests targets increasing F-16's combat capability*. Photo and caption: AEDC PHOTO # 84-1128. *High Mach* issues: November 1980; December 1980; February 1981; March 1982; July 1982; February 1983; March 1983; January 1984; May 1985; January 1986; August 1986; March 1987; July 1987; August 1987; May 1988; June 1988; September 1988; October 1989; Oct. 7, 2005; April 21, 2006; Spring/Summer 1992 Test Highlights; Fall/Winter 1989 Test Highlights; Winter/Spring 1991 Test Highlights; Spring 1992 Test Highlights; Summer 1992 Test Highlights.

**F-22A Raptor (75)** – AEDC news releases: 90-315; 91-103; 91-133; 92-061; 92-091; 92-177; 92-205; 92-242; 92-257; 93-142; 93-143; 93-144; 93-274; 94-012; 94-038; 94-049; 94-134; 94-200; 95-018; 95-019; 95-050; 95-090; 95-130; 95-184; 96-037; 96-041; 96-062; 96-084; 96-090; 96-147; 97-060; 97-062; 97-066; 97-067; 97-115; 97-179; 98-0108; 98-073; 98-100; 98-118; 98-131; 98-153; 98-155; 98-156; 98-158; 98-160; 99-154; 99-262; 2000-002; 2000-020; 2000-057; 2000-114; 2000-118; 2000-135; 2000-169; 2000-219; 2000-231; 2000-248; 2000-281; 2000-311; 2000-314; 2000-344; 2001-032; 2001-064; 2001-080; 2001-082; 2001-084; 2001-181; 2001-221; 2001-242; 2001-262; 2001-298; 2001-348; 2001-368; 2001-403; 2001-407; 2002-036; 2002-084; 2002-184; 2002-238; 2003-029; 2003-327; 2004-303; 2005-053; *Rail-launched missile from a maneuvering aircraft; F-22 engine completes qualification test milestone; F-111 wind tunnel test data to benefit F-22 and Joint Strike Fighter tests; Aeropropulsion testing: Readyng the F-22's F119-PW-100 engine; Aerodynamics testing: Readyng the F-22's airframe and stores; The AEDC and Pratt and Whitney alliance; Modeling and Simulation testing at AEDC*. *High Mach* issues: June 1990; July 1990; December 1990; Feb. 28, 2002; April 17, 2003; May 1, 2003; Oct. 9, 2003; Sept. 23, 2004. Winter/Spring 1991 Test Highlights; Spring 1992 Test Highlights; Summer 1992 Test Highlights. Gallery of photos from Edwards AFB. Lockheed Martin fact sheet.

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# Acronym List

<b>16S</b>	16-foot supersonic wind tunnel	<b>AMRAAM</b>	Advanced Medium Range Air-to-Air Missile
<b>16T</b>	16-foot transonic wind tunnel	<b>AMSC</b>	Advanced Missile Signature Center
<b>4T</b>	4-foot transonic wind tunnel	<b>AMT</b>	Accelerated Mission Test
<b>A&amp;S</b>	Aging and Surveillance	<b>APTU</b>	Aerodynamic and Propulsion Test Unit
<b>AAAM</b>	Advanced Air-to-Air Missile	<b>ARDC</b>	Air Force Research and Development Command
<b>AAF</b>	Army Air Forces	<b>ARO</b>	Arnold Research Organization
<b>ACES II</b>	Advanced Concept Ejection Seat	<b>ARPA</b>	Advanced Research Projects Agency
<b>ACS</b>	A joint venture of Computer Sciences Corp., DynCorp and General Physics	<b>ASD</b>	Aeronautical Systems Division
<b>AEDC</b>	Arnold Engineering Development Center	<b>ASTF</b>	Aeropropulsion Systems Test Facility
<b>AFB</b>	Air Force Base	<b>ATA</b>	Aerospace Testing Alliance
<b>AFFTC</b>	Air Force Flight Test Center	<b>AWACS</b>	Airborne Warning and Control System (E-3A Sentry)
<b>AFMC</b>	Air Force Materiel Command	<b>AXAF-I</b>	Advanced X-ray Astrophysics Facility-Imaging
<b>AFOSR</b>	Air Force Office of Scientific Research	<b>BATES</b>	Ballistic Test Evaluation System
<b>AFRL</b>	Air Force Research Laboratories	<b>BDRF</b>	Bidirectional Reflectance Distribution Function
<b>AFRSI</b>	Advanced Flexible Reusable Surface Insulation	<b>BLU</b>	Bomb Live Unit
<b>AFSC</b>	Air Force Systems Command	<b>BMDO</b>	Ballistic Missile Defense Organization
<b>AFSEO</b>	Air Force Seek Eagle Office	<b>BMW</b>	Bavarian Motor Works
<b>AFT</b>	Augmentor Fan Temperature	<b>BRAC</b>	Base Realignment and Closure Commission
<b>AGARD</b>	Advisory Group for Aeronautical Research and Development	<b>BTU</b>	British Thermal Unit
<b>AGM</b>	Air-to-Ground Missile	<b>CADDMAS</b>	Computer Assisted Dynamic Data Measurement and Acquisition System
<b>AIAA</b>	American Institute of Aeronautics and Astronautics	<b>Caltech</b>	California Institute of Technology
<b>AIDAC</b>	Advanced Instrumentation Data and Control System	<b>CCD</b>	Charge-Coupled Device
<b>AIM</b>	Air Intercept Missile	<b>CDA</b>	Concept Demonstration Aircraft
<b>AIP</b>	Aerodynamic Interface Plant	<b>CDR</b>	Critical Design Review
<b>ALCM</b>	Air-Launched Cruise Missile	<b>CED</b>	Continuing Engineering Development
<b>AMC</b>	Air Mobility Command	<b>CEV</b>	Crew Exploration Vehicle

## Acronym List

<b>CFD</b>	Computational Fluid Dynamics	<b>FAA</b>	Federal Aviation Administration
<b>CFI</b>	Computational Flow Imagery	<b>FBM</b>	Fleet Ballistic Missile
<b>CIP</b>	Component Improvement Program	<b>FFI</b>	Fixed-Foam Insulation
<b>CLV</b>	Crew Launch Vehicle	<b>FET</b>	Fighter Engine Team
<b>COI</b>	Conflict of Interest	<b>FPQ</b>	Full Production Qualification
<b>CRDA</b>	Cooperative Research and Development Agreement	<b>FT</b>	Fischer-Tropsch
<b>CSC</b>	Computer Sciences Corp.	<b>FTI</b>	Fast Tactical Imagery
<b>CSM</b>	Command Service Module	<b>GALCIT</b>	Guggenheim Aeronautical Laboratory of the California Institute of Technology
<b>CTOL</b>	Conventional Take Off and Landing	<b>GATV</b>	Gemini Agena Target Vehicle
<b>CTS</b>	Captive Trajectory System	<b>GBU</b>	Guided Bomb Unit
<b>CV</b>	Carrier Variant	<b>GE</b>	General Electric
<b>CVM</b>	Change Verification Motor	<b>GHQ</b>	General Headquarters
<b>DARPA</b>	Defense Advanced Research Projects Agency	<b>GLCM</b>	Ground-Launched Cruise Missile
<b>DEC</b>	Digital Electronic Control	<b>GLS</b>	GPS Landing System
<b>DIA/DT</b>	Defense Intelligence Agency/ Directorate for MASINT and Technical Collection	<b>GOES-M</b>	Geostationary Operational Environmental Satellite-M
<b>DoD</b>	Department of Defense	<b>GPS</b>	Global Positioning System
<b>DTF</b>	Diagnostic Test Facility	<b>HAAS</b>	High-Angle Automated Sting
<b>EA</b>	Engine Alliance (Pratt & Whitney and General Electric)	<b>HARM</b>	High-Speed Anti-Radiation Missile
<b>ECM</b>	Electronic Counter Measure	<b>HRSI</b>	High-temperature Reusable Surface Insulation
<b>EEC</b>	Extendable Exit Cone	<b>ICBM</b>	Intercontinental Ballistic Missile
<b>EELV</b>	Evolved Expendable Launch Vehicle	<b>IOC</b>	Initial Operating Capability
<b>EFTC</b>	Engine Fan Temperature Control	<b>IFR</b>	Initial Flight Release
<b>EMD</b>	Engineering and Manufacturing Development	<b>IIA</b>	Information International Associates, Inc.
<b>ENEC</b>	Extendable Nozzle Exit Cone	<b>IPE</b>	Increased Performance Engine
<b>EO/IR</b>	Electro-optical/Infrared	<b>IPSM</b>	Improved Performance Space Motor
<b>ESA</b>	European Space Agency	<b>ISR</b>	Initial Service Release
<b>ESP</b>	Electronically Scanned Pressure	<b>ISS</b>	International Space Station
<b>ETF</b>	Engine Test Facility	<b>IUS</b>	Inertial Upper Stage
<b>ETOPS</b>	Extended Twin-Engine Operations	<b>IVA</b>	Impact, Vibration and Acceleration
		<b>JAA</b>	Joint Aviation Authorities

<b>JASSM</b>	Joint Air to Surface Standoff Missile	<b>NFAC</b>	National Full-scale Aerodynamic Complex
<b>JAST</b>	Joint Advanced Strike Technology	<b>NOAA</b>	National Oceanic and Atmospheric Administration
<b>JDAM</b>	Joint Direct Attack Munition	<b>NSMS</b>	Non-intrusive Stress Measurement System
<b>JPL</b>	Joint Propulsion Laboratory	<b>NSP</b>	National Signatures Program
<b>JSF</b>	Joint Strike Fighter	<b>OCR</b>	Operational Capability Release
<b>JSOW</b>	Joint Stand Off Weapon	<b>OMS</b>	Orbiter Maneuvering System
<b>LANTIRN</b>	Low Altitude Navigation Targeting Infrared for Night	<b>OO-ALC</b>	Ogden Air Logistics Center
<b>LEM</b>	Lunar Excursion Module	<b>OPAD</b>	Optical Plume Anomaly Detector
<b>LFT&amp;E</b>	Live Fire Test and Evaluation	<b>P&amp;W</b>	Pratt & Whitney
<b>LGB</b>	Laser Guided Bomb	<b>PES</b>	Plenum Evacuation System
<b>LITVC</b>	Liquid-Injection Thrust Vectoring System	<b>PFQ</b>	Preliminary Flight Qualification
<b>LPQ</b>	Limited Production Qualification	<b>PFRT</b>	Preliminary Flight Rating Test
<b>LPT</b>	Low Pressure Turbine	<b>PLF</b>	Payload Fairing
<b>LRSLA</b>	Long-Range Service Life Analysis	<b>POW</b>	Prisoner of War
<b>MATS</b>	Materiel Air Transport Service	<b>PQA</b>	Production Quality Assurance
<b>MDA</b>	Missile Defense Agency	<b>PRSE</b>	Propulsion System Rocket Engine
<b>MHD</b>	Magneto-Hydrodynamics	<b>PSP</b>	Pressure Sensitive Paint
<b>MIT</b>	Massachusetts Institute of Technology	<b>PV</b>	Product Verification
<b>MMA</b>	Multi-mission Maritime Aircraft	<b>PWSC</b>	Preferred Weapons Systems Concept
<b>MPRTI</b>	Multi-Platform Radar Technology Insertion Program	<b>PWT</b>	Propulsion Wind Tunnel
<b>MOL</b>	Manned Orbiting Laboratory	<b>R&amp;D</b>	Research and Development
<b>MQT</b>	Military Qualification Test	<b>RAF</b>	Royal Air Force
<b>MRTFB</b>	Major Range and Test Facility Base	<b>RAT</b>	RAM Air Turbine
<b>MSFC</b>	Marshall Space Flight Center	<b>RCS</b>	Radar Cross Section
<b>MSL</b>	Mars Science Laboratory	<b>RCS</b>	Reaction Control System
<b>MTSU</b>	Middle Tennessee State University	<b>RDT&amp;E</b>	Research, Development, Test and Evaluation
<b>MX</b>	Missile Experimental	<b>RPV</b>	Remotely Piloted Vehicle
<b>NATO</b>	North Atlantic Treaty Organization	<b>RR</b>	Rolls-Royce
<b>NAVAIR</b>	Naval Air Systems Command	<b>S&amp;P</b>	Sverdrup & Parcel
<b>NEDS</b>	Nozzle Extension Deployment System	<b>SAF</b>	Standard Archive Format

<b>SAG</b>	Scientific Advisory Group	<b>V/STOL</b>	Vertical/Short Takeoff and Landing
<b>SDD</b>	Systems Development & Demonstration	<b>VKF</b>	von Kármán Gas Dynamics Facility
<b>SERV</b>	Single-Stage Earth Orbital Reusable Vehicle	<b>WSC</b>	Weapon System Contractor
<b>SL</b>	Sea level		
<b>SLBM</b>	Submarine-Launched Ballistic Missile		
<b>SLEP</b>	Service Life Extension Program		
<b>SMART</b>	Smart Material-Actuated Rotor Technology		
<b>SMBR</b>	Sikorsky Bearingless Main Rotor		
<b>SMC</b>	Space and Missiles Systems Center		
<b>SRAM</b>	Short-Range Attack Missile		
<b>SRB</b>	Solid Rocket Booster		
<b>SSC</b>	Stennis Space Center		
<b>SSME</b>	Space Shuttle Main Engine		
<b>SST</b>	Supersonic Transport		
<b>STOL</b>	Short Take Off and Landing		
<b>STOVL</b>	Short Take Off/Vertical Landing		
<b>STS</b>	Space Transportation System		
<b>TAC</b>	Total Accumulated Cycles		
<b>TATCOM</b>	Tactical Tomahawk		
<b>TERCOM</b>	Terrain-Contour-Matching Navigation System		
<b>TPS</b>	Thermal Protection System		
<b>TSP</b>	Temperature Sensitive Paint		
<b>TVC</b>	Thrust Vector Control		
<b>TVCS</b>	Thrust Vector Control System		
<b>UAV</b>	Unmanned Aerial Vehicle		
<b>UCAV</b>	Unmanned Combat Air Vehicle		
<b>USAF</b>	United States Air Force		
<b>UT</b>	University of Tennessee		
<b>UTSI</b>	University of Tennessee Space Institute		
<b>UV-VIS-IR</b>	Ultraviolet, Visible, Infrared		





# Appendix 1

## Camp Forrest

# Camp Forrest

Camp Forrest, an active Army post between 1941 and 1946, was one of the U.S. Army's largest training bases during World War II. However, Camp Forrest, named after Civil War Confederate General Nathan Bedford Forrest, was originally known as Camp Peay.

In 1926, the state of Tennessee built a National Guard camp on a strip of land east of Tullahoma. Annual maneuvers at the camp, named for Tennessee Governor Austin Peay, could accommodate 2,500 men.

The military buildup that began in the late 1930s took form in the 1940s. New training centers were established, and manpower was strengthened. One such training center was known as Camp Forrest. The camp, just beyond old Camp Peay, was to become the Army's largest cantonment. The camp would, at completion, cover 10 square miles, crisscrossed by 55 miles of roads. Plans were made for 20,000 troops to be trained at Camp Forrest; however, revisions were continually being made. Between September 1942 and March 1944, there were never less than 50,000 troops stationed at Camp Forrest. During the summer maneuvers of 1941, as many as 70,000 troops were stationed in and around the area. Total number of troops used in 1943 maneuvers was 113,000.

The first troops to move into Camp Forrest were 1,000 men of the Tennessee National Guard 181st Field Artillery Regiment.

The much proclaimed Major General George S. Patton brought his 2nd Armored Division – "Hell on Wheels" – from Ft. Benning, Georgia, which gave the war games an added boost.

William Northern Field became a part of Camp Forrest and the 2nd Army summer maneuvers. The field was



Camp Forrest became a POW camp on May 12, 1942.

used as a training site for crews of multi-engined B-24 bombers of the Army Air Force. During the Camp Forrest era, many air units moved in and out of Northern Field.

The Camp Forrest area was ideally situated with hills, valleys, streams and springs. There were forests and open fields, offering more tactical training opportunities than other installations. Camp Forrest was a training center for infantry and artillery, engineering and signal units. Among the famous units stationed here was the 2nd Ranger Battalion, handpicked in July 1943. The 2nd Battalion later became distinguished in scaling the 90 foot bluffs at Omaha Beach to overtake the enemy in the Normandy landings.

Officially, Camp Forrest became a Prisoner of War (POW) camp on May 12, 1942. The job of the camp was to receive, house, secure and administrate all POWs.

Soon it became necessary to use these people as a labor force, both within the camp and in the surrounding communities. At the camp, the prisoners worked in such facilities as the general hospital, the bakery, kitchens and the automotive shop. They also assisted with the local agricultural crops.

The first prisoners were captured in North Africa. Later, Italian and Japanese soldiers were added to the camp. There were 12 camps for prisoners at the height of the World War II conflict. Camp Forrest received more than 22,000 POWs during the war. The last POW left Camp Forrest on April 13, 1946.

The Camp Forrest era ended with the close of World War II. The camp was declared surplus property in 1946 and was turned over to the Mobile District Engineers. On July 12, 1946, six, two-story barracks were torn down and sent to the Altoona Dam Project in Cartersville, Georgia, marking the beginning of a long dismantling process. Camp Forrest was eventually stripped, leaving nothing but roads, brick chimneys and concrete foundations.



One of the guard towers at Camp Forrest.



**Appendix 2**  
**Unitary Wind Tunnel and**  
**Air Engineering Development Center**  
**Act of 1949**

# Unitary Wind Tunnel and Air Engineering Development Center Act of 1949

Public Law 415 – 81st Congress  
Chapter 766 – 1st Session  
S.1267

## AN ACT

To promote the national defense by authorizing a unitary plan for construction of transonic and supersonic wind tunnel facilities and the establishment of an Air Engineering Development Center.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

### TITLE I

Sec. 101. The National Advisory Committee for Aeronautics (hereinafter referred to as the “Committee”) and the Secretary of Defense are hereby authorized and directed jointly to develop a unitary plan for the construction of transonic and supersonic wind tunnel facilities for the solution of research, development and evaluation problems in aeronautics, including the construction of facilities at educational institutions within the continental limits of the United States for training and research in aeronautics, and to revise the uncompleted portions of the unitary plan from time to time to accord with changes in national defense requirements and scientific and technical advances. The Committee and the Secretaries of the Army, the Navy and the Air Force are authorized to proceed with the construction and equipment of the facilities in implementation of the unitary plan to the extent permitted by appropriations pursuant to existing authority and the authority contained in titles I and II of this Act. Any further implementation of the unitary plan shall be subject to such additional authorizations as may be approved by Congress.

Sec. 102. The Committee is hereby authorized, in implementation of the unitary plan, to construct and equip transonic or supersonic wind tunnels of a size, design and character adequate for the efficient conduct of experimental work in support of long-range fundamental research at educational institutions within the continental United States, to be selected by the Committee, or to enter into contracts with such institutions to provide for such construction and equipment, at a total cost not to exceed \$10,000,000: Provided, That the Committee may, in its discretion, after consultation with the Committees on Armed Services of both Houses of the Congress, vest title to the facilities completed pursuant to this Section in such educational institutions under such terms and conditions as may be deemed in the best interests of the United States.

Sec. 103. (a) The Committee is hereby authorized to expand the facilities at its existing laboratories by the construction of additional supersonic wind tunnel, including building, equipment and accessory construction, and by the acquisition of land and installation of utilities.

(b) There is hereby authorized to be appropriated such sums as may be necessary to carry out the purposes of this section, but not to exceed \$136,000,000.

(c) The facilities authorized by this section shall be operated and staffed by the Committee but shall be available primarily to industry for testing experimental models in connection with the

development of aircraft and missiles. Such tests shall be scheduled and conducted in accordance with industry’s requirements and allocation of laboratory time shall be made in accordance with the public interest, with proper emphasis upon the requirements of each military service and due consideration of civilian needs.

Sec. 104. The Secretary of the Navy is hereby authorized, in implementation of the unitary plan, to expand the naval facilities at the David W. Taylor Model Basin, Carderock, Maryland, by construction of a wind tunnel, including buildings, equipment, utilities, and accessory construction, at a cost not to exceed \$6,600,000.

Sec. 105. The Committee shall submit semi-annual written reports to the Congress covering the selection of institutions and contracts entered into pursuant to section 102 of this title together with other pertinent information relative to the Committee’s activities and accomplishments thereunder.

Sec. 106. This title may be cited as the “Unitary Wind Tunnel Plan Act of 1949.”

### TITLE II

Sec. 201. The Secretary of the Air Force is hereby authorized to establish an Air Engineering Development Center, and to construct, install and equip (1) temporary and permanent public works, including housing accommodations and community facilities for military and civilian personnel, buildings, facilities, appurtenances, and utilities; and (2) wind tunnels in implementation of the unitary plan referred to in Title I of this Act; and to maintain and operate the public works and wind tunnels authorized by Title II of this Act.

Sec. 202. To accomplish the purpose of this title, the Secretary of the Air Force is authorized to acquire lands and rights pertaining thereto, or other interest therein, including the temporary use thereof, by donation, purchase, exchange of Government-owned lands, or otherwise, and construction under this title may be prosecuted without regard to section 3648, Revised Statutes, as amended.

Sec. 203. The Secretary of the Air Force is authorized to employ such civilian personnel as may be necessary to carry out the purposes of this title without regard to the limitation on maximum number of employees imposed by section 14 (a) of the Federal Employees Pay Act of 1946 (5 U.S.C. 947 (g)).

Sec. 204. There is hereby authorized to be appropriated, out of any moneys in the Treasury not otherwise appropriated, to remain available until expended when so specific in the appropriation act concerned, (a) not to exceed \$100,000,000 for the establishment and for initial construction, installation and equipment of the Air Engineering Development Center authorized in this title, including expenses for necessary surveys and acquisition of land, and (b) such sums as may be necessary to carry out the other purposes of this title.

Sec. 205. This title may be cited as the “Air Engineering Development Center Act of 1949”

Approved October 27, 1949



# **Appendix 3 Historic Letters**

**Editor's Note:** The documents that appear in section came from two sources. Pages 221-227 came from the files of the AEDC Historian David Hiebert, while pages 228-235 were given to the Public Affairs office by AEDC Fellow Bob Dietz. In both cases, the documents were retyped and formatted to match the originals as closely as possible.

DEPARTMENT OF THE AIR FORCE  
AIR FORCE HISTORICAL RESEARCH AGENCY  
MAXWELL AIR FORCE BASE, ALABAMA

HQ AFHRA/RSO  
600 Chennault Circle  
Maxwell AFB AL 36112-6424

7 June 1994

AEDC/HO  
ATTN: Dr. David M. Hiebert  
100 Kindel Drive, Suite B330  
Arnold AFB TN 37389-2330

Dear Dr. Hiebert

Reference your 3 June 1994 fax regarding redesignation of Arnold Engineering Development Center.

As you can infer from the attached chronology (attachment 1), there was an installation known as the Arnold Engineering Development Center and an organization with the same name. Despite the ideological designation, the organization's lineage is not that of the installation.

The installation was authorized as the Air Engineering Development Center by Public Law 415, 81<sup>st</sup> Congress, 19 Oct 1949. On 9 Nov 1949, the Secretary of the Air Force announced that the center would be built at Camp Forrest, Tennessee. On 10 Feb 1950, the Air Engineering Development Center was redesignated the Arnold Engineering Development Center (DAF GO#23, 7 Mar 1950, attachment2). On 14 Nov 1950, the center was placed on active status by HQ USAF, and on 25 Jun 1951, President Harry S. Truman dedicated the Arnold Engineering Development Center. The installation was unofficially called Arnold Air Force Station for many years before 20 April 1979, when its name was officially changed from Arnold Engineering Development Center to Arnold Air Force Station (DAF SO#GA-36, 22May 1979, attachment 3). On 15 Sep 1987, Arnold Air Force Station was redesignated Arnold Air Force Base (SO#G-4, HQ AFSC, 7 Oct 1987, attachment4).

The organization was established at Wright-Patterson AFB, OH, on 1 Jan 1950 as the Air Engineering Development Division (DAF Ltr 322 [AFOOR 457f] 30 Dec 1949, attachment 5; GO#2, HQ Air Engineering Development Division, 1 Jan 1950). In mid-November 1950, the division moved from Ohio to the Arnold Engineering Development Center, Tullahoma, Tennessee (SC-OS-18, 16 Nov 1950; DAG Letter 25 Oct 1950; DAF Movement Order Directive AFOOP-OC 570.5, 25 October 1950; DAF Movement Order Directive AFOOP-OC 570.5, 25 Oct 1950). On 3 Aug 1951, the Air Engineering Development Center was redesignated the Arnold Engineering Development Center, a name the organization continues to bear (DAF Ltr 322 [AFOMO 404g] 27 Jul 1951, attachment 6; GO#32, HQ ARDC, 31 Jul 1951, attachment 7).

## Historic Letters

Apparently, from August 3, 1951 through April 20, 1979, both the installation and the organization had the same designation, but remained separate entities. This was recognized as early as Oct 1951 in ARDC Regulation 22-6, 9 Oct 1951, which stated "The mission of the Arnold Engineering Development Center is to construct and operate the Arnold Engineering Development Center, Tullahoma, Tennessee..." (attachment 8).

Please do not confuse the name of the installation with the lineage of the organization. There should be no confusion over the lineage of the organization. The fact that the organization and the installation had the same name for years does not make their lineages "tangled".

You also asked if there was an advantage for an installation to be known as a base rather than as a station. The same question was raised a few years ago about Gunter Air force Station, which was changed to Gunter Air Force Base before it became the Gunter Annex, Maxwell AFB. We can only speculate. For a time, installations without active runways, such as Gunter, were known as stations rather than bases. Some may surmise that, in this era of installation closures, an Air Force base, but more likely the change was for consistency.

I hope this information answers your questions satisfactorily.

Sincerely,

Daniel L. Haulman  
Historian

### 8 Attachments:\*

1. AEDC chronology
2. DAF GO#23, 7 Mar 1950
3. DAF SO#GA-36, 22 May 1979
4. SO#G-4, HQ AFSC, 7 Oct 1987
5. DAF Ltr 322 [AFOOR 467f] 30 Dec 1949
6. DAF Ltr 322 [AFOMO 404g] 27 Jul 1951
7. GO#32, HQ ARDC, 31 Jul 1951
8. ARDC Reg 22-6, 9 Oct 1951

\* Attachments 3 and 8 are not included in this Appendix.



Chronology of Arnold Engineering Development Center

19 Oct 1949 Public Law 415 of 81<sup>st</sup> Congress authorized as Air Engineering Development Center

9 Nov 1949 Secretary of the Air Force announced that the Air Engineering Development Center would be built at Camp Forrest Tennessee

1 Jan 1950 the Air Engineering Development Division was established at Wright-Patterson AFB (DAF Ltr 322[AFOOR 457f] 30 Dec 1949, GO#2, HQ Air Engineering Development Division, 1 Jan 1950

10 Feb 1950 Air Engineering Development Center redesignated Arnold Engineering Development Center (DAF GO#23, 7 Mar 1950

14 or 15 November 1950 Air Engineering Development Division moved from Wright-Patterson AFB, OH, to Tullahoma, Tennessee to an installation known as the Arnold Engineering Development Center, (SC-OS-18, 16 Nov 1950; DAF Letter 25 October 1950; DAF Movement Directive AFOOP-OC 570.5, 25 Oct 1950)

14 Nov 1950 Arnold Engineering Development Center placed on active status by HQ USAF

25 Jun 1951 President Harry S. Truman dedicated the Arnold Engineering Development Center

3 August 1951 Air Engineering Development division was redesignated the Arnold Engineering Development Center (DAF letter 322 (AFOMO 404g) 27 Jul 1951; GO#32, HQ ARDC, 31 Jul 1951). The installation and the organization had the same name.

20 April 1979 Installation's name changed from Arnold Engineering Development Center to Arnold Air Force Station (DAF SO#GA-36, 22 May 1979). The organization remained the Arnold Engineering Development Center

15 Sep 1987 Arnold Air Force Station redesignated Arnold Air Force Base (SO#G-4, HQ AFSO 7 Oct 1987)

**Historic Letters**

DEPARTMENT OF THE AIR FORCE  
WASHINGTON

GENERAL ORDERS)  
NO. 23)

7 March 1950

The Air Force installation situated at the location indicated has been redesignated effective 10 February 1950:

<u>Name</u>	<u>Formerly known as</u>	<u>Location</u>
Arnold Engineering Development Center (In honor of General of the Air Force Henry H. Arnold, 02255)	Air Engineering Development Center	Tennessee

BY ORDER OF THE SECRETARY OF THE AIR FORCE:

OFFICIAL:

HOYT S. VANDENBERG  
Chief of Staff, United States Air Force

L.L. Judge  
Colonel. USAF  
Air Adjutant General

DISTRIBUTION

D

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Addendum\*:

Air Engineering Development Center, Tennessee, was redesignated Arnold Engineering Development Center on 10 February 1950.

-DL

\*Addendum appears as handwritten notation at bottom of our copy of General Order 23.

DEPARTMENT OF THE AIR FORCE  
WASHINGTON

30 DECEMBER 1949

322 (AFOOR 467f)

SUBJECT: Establishment of the Air Engineering Development Division

TO: Commanding Generals,  
Air Engineering Development Division  
Air Materiel Command

1. Effective 1 January 1950, the Air Engineering Development Division is established with station at Wright-Patterson Air Force Base, Dayton, Ohio.

a. The Air Engineering Development Division will operate as a separate operating agency under the direct control of the Chief of Staff, USAF, with the procedural functions and responsibilities of a major air command.

b. The "Headquarters, Air Engineering Development Division" will be designated and organized by the Commanding General, Air Engineering Development Division as a table of distribution unit.

c. The Headquarters, Air Engineering Development Division is attached to Air Materiel Command for administrative and logistic support in accordance with joint use agreement between the Commanding General, Air Materiel Command and the Commanding General, Air Engineering Development Division.

2. Administrative and housekeeping equipment is authorized in accordance with T/A 1-1.

3. Funding for the Air Engineering Development Division will be accomplished directly to the Air Engineering Development Division by Headquarters, USAF, effective 1 January 1950. Funding programs will be established accordingly.

4. Statistical servicing responsibility will be assumed by Air Materiel Command.

5. An acknowledgment report of this action will be submitted to Headquarters USAF by means of the Air Force Organization Status Change Report (Reports control Symbol AF-SC-02) in compliance with current instructions.

BY ORDER OF THE SECRETARY OF THE AIR FORCE:

L.L. JUDGE  
Colonel, USAF  
Air Adjutant General

50-7876, AF

**Historic Letters**

DEPARTMENT OF THE AIR FORCE  
WASHINGTON 25, D.C.

322 (AFOMO 404g)

SUBJECT: (Unclassified) Redesignation of the Air Engineering  
Development Division

TO: Commanding General, Air Research and Development Command

1. Effective within forty-five (45) days after the date of this letter, the following establishment and unit will be redesignated.

Present Destination

New Destination

Air Engineering Development  
Division

Arnold Engineering Development  
Center

Hq, Air Engineering Development  
Division

Hq, Arnold Engineering Develop-  
ment Center

2. When the action directed herein has been accomplished, report will be made to headquarters USAF by means of the Air Force Organization Status change Report (Reports control Symbol AF-SO-02) in compliance with current instructions.

3. Forty (40) copies of the order issued pursuant to this letter will be forwarded to the Air Adjutant General, headquarters USAF,  
ATTENTION: Publishing Division, Washington 25, D.C.

BY ORDER OF THE SECRETARY OF THE AIR FORCE

K.E.THIEBAUD  
Colonel, USAF  
Air Adjutant General

DISTRIBUTUIB:

Dept of Army	(21)
Chiefs of Tech Services	(40)
Hq USAF	(121)
Air Materiel Command, ATTN: MCAGXP	(50)
Air University Library	(2)
Air Materiel areas	(5)
Specialized depot groups	(3)
Air Research and Development Command	(30)

HEADQUARTERS  
 AIR RESEARCH AND DEVELOPMENT COMMAND  
 5 West Baltimore Street  
 Baltimore 1, Maryland

GENERAL ORDERS)  
 NUMBER 32)

31 July 1951

REDESIGNATION OF AIR ENGINEERING DEVELOPMENT DIVISION-----I  
 REDESIGNATION OF TABLE OF DISTRIBUTION UNIT-----II  
 REASSIGNMENT OF TABLE OF DISTRIBUTION UNIT-----III  
 GENERAL INSTRUCTIONS-----IV

I. REDESIGNATION OF AIR ENGINEERING DEVELOPMENT DIVISION.

-1. Pursuant to letter, Department of the Air Force, file 322 (AFOMO 404g) dated 27 July 1951, the Air Engineering Development Division is redesignated the Arnold Engineering Development Center, effective 3 August 1951.

II. REDESIGNATION OF TABLE OF DISTRIBUTION UNIT. -1.

Concurrent with the redesignation action in Section I above, and pursuant to authority contained in letter. Department of the Air Force, File 322 (AFOMO 404g), dated 27 July 1951, the following Table of Distribution Unit is redesignated, effective 3 August 1951, with assignment as specified.

<u>OLD DESIGNATION</u>	<u>NEW DESIGNATION</u>	<u>ASSIGNMENT</u>
Headquarters, Air Engineering Development Division	Headquarters, Arnold Engineering Development Center	Air Research and Development Command

III. REASSIGNMENT OF TABLE OF DISTRIBUTION UNIT. Pursuant to authority contained in Air Force Regulations 20-52 and 20-38, the 6560<sup>th</sup> Air Base Squadron is relieved from assignment to the Air Engineering Development Division, and assigned to the Arnold Engineering Development Center, without change of station, effective 3 August 1951.

IV. GENERAL INSTRUCTIONS.-1. The following instructions are applicable to the units listed in Section II and III above.

2. Personnel will be furnished from sources under the control of the Commanding General, Arnold Engineering Development Center and will be administered under the provisions of Air Force Regulation 40-2 and Air Force Regulation 35-68

3. Equipment is authorized in accordance with Tables of Allowance 1-1 "Administration and Maintenance", dated 4 October 1948, 1-38 "Development and Experimental", dated 7 February 1947, and 1-75 "General Purpose Automotive Vehicles", dated 21 May 1948, and changes thereto.

DEPARTMENT OF THE AIR FORCE

Washington

Meeting of AD HOC Committee on Master Plan for AEDC

17 April 1950

1. The following members of the Committee were present:

Major General Grandison Gardner	Hq, USAF, Chairman
Major General F.O. Carroll	AEDD
Major General James B. Newman, Jr.	Hq, USAF
Colonel Lebbeus Woods	AEDD

The following people were also present:

Colonel David M. Dunne	Corps of Engineers
Colonel McD. D. Weinert	Corps of Engineers
Mr. Roy SHoults	AEDD
Major John T. Trotter	AEDD
Major Vincent T. Ford	AEDD
Gen. Lewis T. Ross	Sverdrup and Parcel
Mr. E.M. McDaniel	Sverdrup and Parcel
Mr. J.H. Spangole	AEDD
Mr. E.L. Rankin	AEDD

2. General Carroll opened the meeting with a general review of the construction picture as it presently exists. It was agreed by all concerned that the present dam location satisfies all requirements, that it is the best one from a seismographic standpoint. A discussion of the drainage problem at the site followed. It was agreed that even though certain drainage difficulties will have to be overcome by locating the main AEDC area in its present position, little or no advantage would follow by changing the location.

3. General Ross reviewed the Preliminary Master Plan, dated 15 April 1950. The road, railroad, and bridge construction problems were reviewed as well as the locations proposed for the main test facilities and accompanying structures.

4. A motion was made by General Newman and seconded by Col. Woods that:

The proposed access road (the entire Route "B", as set for in Exhibit 1 of the "Access Road Study for AEDC," dated 14 April 1950, and prepared by the Corps of Engineers) be approved by the Committee on the Master Plan, and that the road shall be constructed on Government owned land insofar as it is possible.

5. The location of the railroad was next considered by the Committee. After some discussion it was agreed that the District Engineer will obtain additional data and cost figures and will present his recommendations on the location of the railroad to the Committee at its next meeting.

6. The problem of cooling water was discussed. It was agreed that this problem, being of major importance, will require further study.

7. The problem of noise was discussed. It was generally agreed that the noise factor would be an important one but that, with present noise-dampening processes and the distance of the test facilities from the four principal surrounding communities, there will be no difficulty in overcoming the noise problems.

8. The main coordinates for AEDC have now been staked at the site. The key point is at the coincidence of the State grid system and that of the AEDC grid system. The AEDC grid system parallels the site layout and is 15 degrees E of the State N-S grid system.

9. A motion was made by Col. Woods, seconded by Col. Weinert that:

a. The Preliminary Master Plan, dated 15 April 1950, be approved by the

Master Planning Committee

b. The proposed "block" locations of the test facilities be approved as set forth in the Preliminary Master Plan.

c. Additional data on the location of the railroad be presented to the Committee at its next meeting for final approval.

10. A motion was made by Gen. Gardner, seconded by Gen. Newman that:

a. The proposed housing location adjacent to Tullahoma be approved contingent upon action being taken by local agencies to impose proper building restrictions and zoning of adjacent privately owned areas.

11. The question of whether brick or concrete architectural treatment should be decided upon was presented to the Committee by Col. Woods. Estimates prepared by the architect-engineers and submitted to the District Engineer concluded that brick is the cheaper type of construction and that in any event the difference in cost between the two types of treatment would be reasonable. A motion was made by Gen. Carroll, seconded by Col. Woods that:

a. The Committee on the Master Plan adopt brick as the basic architectural treatment for all appropriate buildings.

12. A discussion of the ownership and control of the road through the site followed Arguments were advanced in favor of Federal Government control and ownership of the road, and all access rights thereto, as against State control. It was agreed that we should assume that the road will be Federally owned, maintained and operated, giving the State right of entry for construction and permitting public access at the discretion of the United States Government.

13. There being no further business, the meeting adjourned, the next meeting to be held upon call of the Chairman.

Grandison Gardner  
Major General, USAF  
Chairman  
Air Force Base Development Board

DEPARTMENT OF THE AIR FORCE

Washington

27 July 1950

**Subject:** Management and Operational Plan for AEDC

**To:** ARO, Inc.  
Second Floor  
522 Olive Street  
St. Louis, Missouri

1. It is requested that ARO, Inc., prepare a plan indicating the manner in which the Corporation expects to accomplish the management and operational functions for the Arnold Engineering Development Center.

2. The plan to be prepared should include a one through five year period indicated by year, the various phases expected to be accomplished. The entire plan should parallel the construction program assuming that upon completion of a given facility and acceptance by the Air Force the facility will be released to ARO, Inc., for operation and/or management.

3. The Corporation's five year plan should include, but not be limited to the following:

- a. The mission of ARO, Inc., the charter and scope of the operation.
  - b. The organizational structure required to accomplish the mission.
  - c. The anticipated functions to be performed in each of the main test facilities along with the supporting utilities, as well as the management overhead.
  - d. The number and type of employees, technical and non-technical required to perform the functions in each facility, supporting utilities and management overhead.
  - e. The schedule for procurement of personnel to perform these functions.
  - f. The training program and methods required to train the personnel who will operate the facilities.
  - g. The salary range believed to be required to attract capable personnel.
  - h. The planned employees benefits such as:
    1. Retirement pay
    2. Sick leave
    3. Annual leave
    4. Promotions
    5. Incentives
    6. Other personnel services in the form of employee relations, recreation, etc.
  - i. Non-expendable item of supplies required or to be furnished by the Air Force and/or any other capital property equipment to be Government Furnished (less vehicles).
  - j. Transportation vehicles by type.
  - k. Re-evaluation of power supply required. (Sverdrup & Parcel computed this some time ago; however, in view of the RDB directive, a re-study of power should be included in this plan).
    - l. Fuel and lubrication required by type.
  - m. The relationship proposed for joint use of the test facilities by industry, universities and/or other departments of National Defense personnel, when one or more of the above agencies are conducting tests in a given facility.
  - n. The manner in which ARO, Inc., plans to provide services to one or more of the agencies referred to in the paragraph above, during their visit to AEDC.
4. It is understood that the above plan will require time to accumulate and present the data, however, as a given phase of the program is completed, it should be forwarded to this Headquarters for review and approval. The entire plan should be



completed within four months. Of course, with experience and time, various phases of the program will be re-tailored to meet new concepts and/or operating requirements.

F.O. Carroll  
Major General, USAF  
Commanding  
Air Engineering Development Division

**HEADQUARTERS**

Arnold Engineering Development Center  
Tullahoma, Tennessee

**Subject:** Revised Planning and Reprogramming for AEDC

**To:** ARO, Inc.

522 Olive Street

St. Louis, Missouri

Thru: Officer-in-Charge, Liaison Office

AEDD (Lt. Col. L.B. Loggins)

1. Reference is made to letter, Headquarters AEDD, 11 October 1950, subject same as above, wherein this office is directed to coordinate the replanning and reprogramming of the facilities at AEDC and to make any necessary revisions in the construction program. Information copy of referenced letter was submitted to your office.

2. It is requested that representatives of your office meet with representatives of other interested offices or agencies that this office 1300 hours 31 October 1950 to consider and approve preliminary replanning and reprogramming of facilities.

3. Representatives attending this conference should be conversant with facilities required and included in the one hundred fifty seven million five hundred thousand dollar (\$157,500,000) authorization and be prepared to furnish most accurate and current requirement for installed equipment and facilities with estimated cost of engineering, designing, inspection, procurement, installation and construction of each facility and/or equipment. Representatives should also be familiar with latest design criteria and authorized to make decisions and/or approve your office the replanning and programming of facilities.

4. Similar letters are being submitted to Deputy for Comptroller, AEDD, Deputy for Operations, District Engineer, Tullahoma District, and Sverdrup & Parcel, Inc.

5. Request comments and advice of attendance at conference be submitted to this office as soon as possible so that agenda may be finalized and all interested offices and agencies advised.

Lebbeus. B. Woods  
Colonel, USAF  
Officer-in-Charge

St. Louis Office  
Room 210, 522 Olive Street  
St. Louis, Missouri

8 August 1950

**Subject:** Target Dates for Completion of the Main Facilities, AEDC

**To:** The Commanding General  
Air Engineering Development Division  
The Pentagon, Room 50368  
Washington 25, D.C.  
Attn: EDD

1. Reference is made to our telephone conversation yesterday and your wire today. The completion dates which were furnished Major Ford by telephone yesterday are as follows:

ETF	Completion to begin testing	April 1952
GDF	Begin calibration	July 1953
PWT	Begin calibration of transonic testing section	January 1954
	Administration and Engineering Building - Ready for occupancy	March 1952
	Warehouse Ready for occupancy	June 1951
	Steam Generator Plant Complete	
	(Preliminary service available early in 1952)	October 1952
	Fire, Police and	
	First Aid Building Complete	October 1951
	Machine Shop	
	(Model shop) Building Complete	April 1952
	Dam and Reservoir Filled partially to provide initial cooling water supply;	
January 1952		
	(final clean up)	July 1952
	Cooling Water System Ready for service	January 1952
	Electrical System First parts of system completed	July 1951
	Completed (Remaining parts completed progressively as required by the technical facility supplied.)	

2. These dates correspond with the ones confirmed by telephone to Major Ford approximately 7 August 1950.

D. R. Shoults  
Director of Engineering

INTRODUCTION

\* \* \* \* \*

The Arnold Engineering Development Center has been established to serve and provide for the ever advancing development needs of Industry and the Military Services. ARO, Inc. has been organized as a prime contractor under the Air Force to provide full management and operational services of the Center, sponsoring continued progress and achievement in the development field of Aeronautics.

The contents of this document present our preliminary outline envisioning management and operational objectives and practice that will facilitate the accomplishment of development goals, maintaining a spirit of service, economy, and efficiency contributory to the best interest of the Air Arm for National Defense.

\* \* \* \* \*

L.J. Sverdrup  
President

MISSION

\* \* \* \* \*

ARO, Inc., as established under the corporate laws of the State of Tennessee, is an organization whose sole function is to completely manage and operate the Arnold Engineering Development Center as a prime contractor for the United States Air Force under the immediate technical direction of the Commanding General, Air Engineering Development Division, Research and Development Command.

Authority

Teletype dated 18 April 1950, enclosed.  
U.S. Air Force Contract AF 33(038)-1228,  
Exhibit "A" enclosed.

Scope

ARO, Inc., as contracted and under the Air Force direction, will completely activate, man, manage, operate and improve the Government-owned installation known as the Arnold Engineering Development Center located at the City of Tullahoma in the State of Tennessee.

In the course of this responsibility it will serve Industry and the Services as a centralized agency, utilizing these highly specialized facilities to provide Static and Flight

- Development testing
- Performance testing
- Acceptance testing
- Compilation of test data & reports
- Accumulation of data
- Consolidation of data
- Interpretation and Translation of data
- Evaluation of data as and requested

Objectives

Materially and effectively reduce the total time required for experimental development of programmed articles towards production items of assured performance ability.

Participate effectively as an element of the Unitary Wind Tunnel Plan for accomplishment of applied research, development and experimentation for the United States Air Force and as directed in the interests of broad programmed objectives. Provide for and serve the experimental development needs of the Aeronautical Industry, the Services, Universities, and research organizations of the Government. Provide for continuous experimental development of self-generated items or fields which are of specific material value to positive objectives of an approved program or sponsored project.

Policy

Provide efficient, effective, economical and flexible operation of the Arnold Engineering Development Facilities to insure the accomplishment of these objectives and assigned duties in order that the best interests of National Defense responsibilities delegated to the Air Force will be served.

**ORGANIZATION**

\* \* \* \* \*

General

The ultimate design of the management and operational organization of ARO, Inc. will be guided toward and in support of the integral objectives of the basic mission and will adjust as required to meet the demands of scientific advancement, experimental and development workloads.

We envision three progressive steps or phases which must be spanned in the course of organization's development. Its transition through these phases necessitates a cautious continual blending of professional and skilled activities objectively toward the expeditious accomplishment of tasks at hand.

Phase I

- Planning, Design Review
- Procurement, Operational requirements
- Training & coordination

Phase II

Acceptance of completed facilities and performance of required tests. Preliminary activation of the Engine Test Facility and certain of the key Central Facilities. Management and operating staff as required. On the job orientation and training. Development programs, projects, orientation and scheduling.

Phase III

Total and final activation. Full scale operation and housekeeping. Development, performance, experimental and acceptance testing in progress.

During the progress of Phases I and II the character of the organization is a cross section of professions, skills and trades blended with the singular or joint activities of other agencies contributing largely to the completion of the Center. The major portion of this activity will not ultimately be concerned in the development test operations of Phase III which follows.

During Phase I and II considerable planning, development and training must be exercised in preparation for and transition to Phase III. The major factor upon which the third phase development must be affected is the scheduled workload and the time factor for its accomplishments.

Without this vital factor it is premature to consider finalizing the organization's design, therefore the organization charts which follow are schematic in nature and subject to change or revision in the course of progress during Phase I, II and III.



# **Appendix 4**

## **AEDC's Men of Vision**

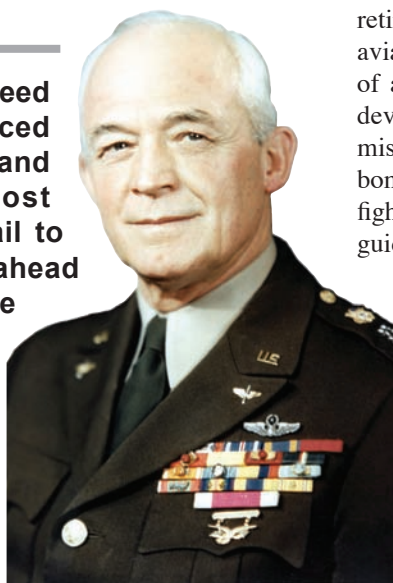
# General of the Air Force Henry Harley “Hap” Arnold



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**“... Most important of all, we will need an ably staffed, adequately financed and properly equipped research and development program. I say most important of all because, if we fail to keep not merely abreast of, but ahead of, technological development, we needn’t bother to train any force, and we needn’t make any plans for emergency expansion; we will be totally defeated before any expansion could take place.”**

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Five-Star General of the Air Force Henry Harley “Hap” Arnold was known for his smile.

However, on Aug. 17, 1945, his face was stern as he called a press conference in the War Department headquarters in Washington, D.C., to discuss “the future.” Many in the press of that era described General Arnold’s conference as “the most important pronouncement in all his years of press conferences.”

General Arnold, who entered West Point as a young cadet in 1903, the same year that the Wright brothers flew the first powered, heavier-than-aircraft at Kitty Hawk, North Carolina, was about to make one of the most important declarations about the future of air dominance and security that the nation would ever hear.

Ironically, it was the love of horses and the thunderous charge of the horse brigade coupled with the wide gold stripe upon uniform pants that drove

his desire to become a member of the calvary.

Then, 42 years later, it was the roar and “horsepower” of the military’s finest aircraft and his desire to ensure the future of the Air Force that led to his concluding paragraph in that momentous press conference.

Arnold stated, “... Most important of all, we will need an ably staffed, adequately financed and properly equipped research and development program. I say most important of all because, if we fail to keep not merely abreast of, but ahead of, technological development, we needn’t bother to train any force, and we needn’t make any plans for emergency expansion; we will be totally defeated before any expansion could take place.”

These words came three days after V-J Day, more than two weeks before the Japanese surrendered aboard the battleship *Missouri* and the day before Arnold announced his plans to

retire. The story of his life as an Army aviator is the story of the evolution of airpower from its infancy to the development of the first long-range missiles in 1918, the first long-range bomber in 1934, the first American jet fighter in 1941, and the first television-guided bomb in 1943.

Henry Harley “Hap” Arnold was born on June 25, 1886, in Gladwyne, Pennsylvania. His father, Dr. Herbert A. Arnold, wanted his son to be a minister, but that didn’t really excite the boy’s interest. Arnold managed to obtain the West Point appointment his father had arranged for his oldest son, Tom, who chose to stay at Penn State to get an electrical engineering degree.

Much like his nickname thought to be “Happy,” Arnold was elated to leave the small town and carry on the family’s military heritage. He became a member of the Black Hand,



Arnold as a West Point sophomore in 1905.



a secret organization that managed to keep him in the bottom quarter of his class in discipline. He culminated his career as a prankster by setting off a barrage of fireworks from the roof of an academy barracks – a prank that earned him solitary confinement in his room during visitors' day and cost him the opportunity to visit with the future Mrs. Arnold, Eleanor Pool.

Arnold expected to be assigned to the cavalry upon his graduation in 1907 but found himself in the infantry instead. Interestingly, aviation was his fourth choice.

Accompanied by his congressional representative and one of Pennsylvania's senators, he appeared before the Army Adjutant General, demanding the assignment be changed. The general told him that only the Secretary of War could do that and he was in the Philippines.

Arnold immediately volunteered to go there. He missed the Secretary but found himself in an exciting new job: surveying.

For two years, Arnold tramped through the jungles of Luzon and Corregidor preparing topographical

maps. He lived the life of an explorer, setting up base camps to work from and living off the land. It was excellent training because he and another lieutenant were basically responsible only to themselves and had the freedom to do the job the way they saw fit.

He left for his next assignment at Governors Island, New York, in 1909, and made the long trip home via Hong Kong, Singapore, Cairo and Paris.

In Paris, he saw an airplane for the first time and was unimpressed. His interest didn't grow even with such luminaries as Glenn Curtiss and the Wrights flying around the level fields of Governors Island. But, a chance opportunity whetted his appetite.

Concerned with promotion to first lieutenant, Arnold took an examination for an opening in the Ordnance Department. While he awaited the results, the War Department asked if he would be willing to become a pilot. Arnold was unsure and asked his commander for advice. The senior soldier told Arnold he knew no better way for a man to kill himself. Arnold sensed the kind of adventure



Top, a 25-year-old Arnold sits at the controls of a Type B two-seater Wright plane while learning to fly under instructions of the Wright brothers at their school in Dayton, Ohio, in 1911. Middle, Arnold and Thomas DeWitt Milling, in 1931. Bottom, Arnold was the first recipient of the Mackay Trophy in 1912. He won a second in 1935.



(Left to right) Capt. Frederick Hennessy, Lt. Henry Arnold, Lt. Roy Kirtland, Capt. Frank Kennedy, Lt. Samuel McLeary, Lt. Harold Geiger, Lt. Thomas Milling and Lt. Louis Rockwell at College Park, Maryland, in 1911. Lieutenants Arnold and Milling were the first to qualify as military aviators, along with Capt. Charles Chandler.



## Henry Harley “Hap” Arnold

he had loved in the Philippines and immediately accepted the Army’s offer.

Arnold and Lt. Thomas DeWitt Milling arrived at the Wrights’ bicycle shop in Dayton, Ohio, in 1911. After extensive training on the ground, Arnold made his first flight on May 3. It lasted seven minutes.

For the next 10 days, he practiced under the watchful eyes of his instructor, Al Welch, and the local undertaker, who sat on his wagon awaiting the inevitable each day. After logging three hours and 48 minutes of flight time, Lt. Arnold received his badge as Military Aviator Number 1.

In 1912, Arnold received the first Mackay Trophy for flying a 42-mile triangular circuit and for establishing a new world altitude record of 6,540 feet. Later that same year, after surviving a horrible crash, he decided to quit flying. He had seen too many friends die, and his nerves were shot. This decision greatly relieved his fiancée, Eleanor. The two were married in 1913.

The couple spent the first three years of married life in the Philippines before returning to Rockwell Field, California. Surrounded again by airplanes, Arnold got flying fever. His wife could no longer stand to see him in so much anguish and encouraged him to fly again. It was all the encouragement he needed.

When World War I broke out in Europe, Arnold was in Panama. He was recalled to Washington to be the chief of the Information Division and, in 1917, became Assistant Director of Military Aviation – the youngest colonel in the Army. He fought hard to get into combat but was turned down because he was indispensable in his job. He always remembered this frustration and made it a point in World War II to get everyone he could some combat experience.

He reverted to his permanent rank of captain after the war and served in various jobs in California, ending up at the Presidio of San

Francisco as the aviation officer for the west coast. Promoted to major, he returned to Rockwell Field in San Diego as commander. There he encouraged Lieutenants Lowell Smith and Paul Richter in developing aerial refueling. The first air-to-air contact refueling took place in June 1923.

In 1925, after graduating from the Army Industrial College, he returned to Washington. There he found himself in the middle of the biggest military trial of the century: Col. Billy Mitchell’s court martial. Arnold plunged headlong into the trial, testifying in Mitchell’s behalf. When the trial was over, he got his reward for speaking out: “exile” to Ft. Riley, Kansas.

In 1928, Hap attended Command and General Staff School at Ft. Leavenworth. It was not a happy year for him, and he became more and more restive as graduation approached. On the final day, he had Eleanor and their three boys waiting in the car with the engine running. As soon as the ceremony ended, he bolted down steps, jumped in the car and drove out the gate as fast as he could. Their destination: Fairfield Air Depot, Dayton, Ohio.

Fairfield was the home of one of Billy Mitchell’s few mistakes – the Barling Bomber. It was the first big bomber and that was its major drawback. Its state-of-the-art engines had too little power, and it couldn’t even



Then Lt. Gen. Arnold with Brig. Gen. Jimmy Doolittle. Doolittle, who led the first bombing raid on Japan and would later work for a superior airframe research and development program.



The meeting between General of the Air Force Henry “Hap” Arnold and a young Dr. Theodore von Kármán in 1923 would later play a role in the 1945 report, *Toward New Horizons* which became the “blueprint for Air Force research and development.” In this photo, Arnold awards von Kármán the Meritorious Service Emblem after the Scientific Advisory Group’s (SAG) first year.

gain enough altitude to surmount the Appalachian Mountains. Arnold tried desperately to get rid of the plane through official channels, but it was such an embarrassment to the

bombardment advocates that Army leaders refused to scrap it. Arnold was not one to stop at a simple “no” answer. If he couldn’t get rid of the plane with approval, he’d find some other way. He sent an obscure message requesting permission to

scrap “one obsolete bomber” and received approval. It wasn’t long before a mysterious fire broke out in the hangar that housed the Barling and completely destroyed both building and plane.

In 1931, Lt. Col. Arnold became the commander of March Field, in Riverside, California. While there, he arranged for the purchase of a huge chunk of the Mojave Desert. He used the Muroc Dry Lake area for training his pilots in combat operations, both air-to-air and bombardment. The land he purchased later became Edwards Air Force Base (AFB).

After commanding the western sector during the “Air Mail Fiasco” in 1934, Arnold led a flight of 10 B-10s from Dayton to Fairbanks, Alaska. On the return trip, the planes flew non-stop from Juneau to Seattle, entirely over water. The press coverage helped massage the bruises the Air Corps had

received in its bout with the air mail, and the flight was topped off by Arnold’s second Mackay Trophy.

On Feb. 11, 1935, Arnold received his first star, skipping the rank of colonel, due to expansion of the Air Corps rank structure associated with the activation of General Headquarters (GHQ) Air Force. In January 1936, he returned to Washington as Assistant Chief of the Air Corps to Maj. Gen. Oscar Westover and replaced him as chief when Westover died in a plane crash in 1938. This was to be Arnold’s last job in the Army – he would be Chief of the Air Corps until his retirement in 1946.

His work during wartime made him a legend in both military and civilian circles. He opened Officer Candidate Schools in Miami Beach hotels that had been emptied by the war, cajoled civilian flying schools into training pilots for the Army long before funds and official approval were available and constantly pushed aircraft manufacturers for more and better equipment. His subordinates called him “Do-it-yesterday Arnold” and he was known to stop junior officers in the hall, tell them to handle a problem and disappear.

In 1923, General Arnold was introduced to Dr. Theodore von Kármán, a Hungarian scientist who later became an instrumental figure in the development of AEDC.

Arnold had found the aeronautics tutor he needed. He became dependent upon von Kármán to inform, educate and guide him during his years in command of the Army Air Corps, later called the Army Air Forces (AAF).

Their relationship grew, and near the end of World War II Arnold asked von Kármán to direct a study of military aeronautical technology and its future, considering the state of the art in Germany, Japan, Russia and all the countries in between them. The result led to the December 1945 report *Toward New Horizons*, which is now considered the “blueprint for Air Force research and development”



**In September 1938, Arnold was sworn in as the Commander of the Army Air Corps.**



**President Truman decorates Arnold on his retirement in 1946.**

## Henry Harley “Hap” Arnold



Arnold's widow, Bee, and sons attend the center's dedication in his memory on June 25, 1951.

and the foundation of AEDC.

The two men first met when Arnold commanded March Field. He had always shown a keen interest in science and even sent several of his officers to classes taught by von Kármán at the California Institute of Technology (Caltech). In 1939, Arnold had asked him what facilities the Air Corps needed for research.

Von Kármán told him they needed a large wind tunnel and added, “Maybe you don’t wish to invest in such a large and revolutionary piece of equipment?”

“On the contrary, that’s exactly what we do want, the highest combination of speed and size,” Arnold replied.

Wright Field’s 20-foot wind tunnel was the result. But Arnold had something bigger in mind.

He wanted the scientist to gather a group of experts to give direction to military research. And at their first meeting, he told them, “The next Air Force is going to be built around scientists – around mechanically minded fellows.”

Arnold received his fifth star as

a general of the Army in December 1945, the only airman ever to attain that rank.

In March 1946, he retired from active duty in an attempt to relax. Hard work had taken its toll on his once-strong body; he had survived five major heart attacks and countless minor ones.

In 1947, after the U.S. Air Force became an independent Service, President Truman made Arnold General of the Air Force. Arnold is the only Airman to hold that rank and the only five-star general to serve in two services at a five-star rank.

On Jan. 15, 1950, a sixth heart attack claimed his life.

Eighteen months later, on his 65th birthday, the Air Engineering Development Center would be dedicated in his name as Arnold Engineering Development Center – a testimony to his foresight, drive and determination. His widow, Bee, and sons attended the dedication of the center in his memory on June 25, 1951.

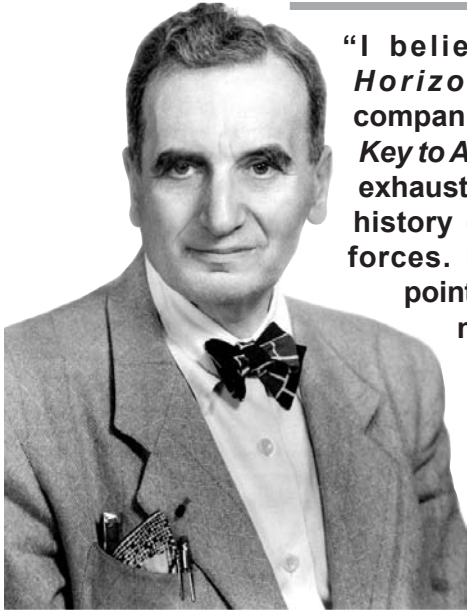
During his aviation career General Arnold made history. By

his retirement, everyone called him “Hap,” a name with dubious origins, yet while the exact origin of his nickname remains a historical mystery, his accomplishments, contributions and pioneering efforts in aviation remain a constant:

- He was the first to demonstrate how the airplane could be used for reconnaissance.
- He was awarded the first military aviator’s badge and expert aviator’s certificate.
- He established a world altitude record of 6,540 feet.
- He promoted innovations such as the aerial forest patrol and in-flight refueling.
- He organized and led 10 B-10 bombers on a historic flight from Ohio to Alaska, flying 18,000 miles round trip and conducted more than 35,000 square miles of aerial surveys of Alaskan territory.

Arnold was enshrined in the National Aviation Hall of Fame in 1967. He was inducted as an honorary AEDC Fellow during the 50th anniversary of the dedication of AEDC in June 2001.

# Dr. Theodore von Kármán



**“I believe that *Toward New Horizons*, together with a companion volume, *Science: The Key to Air Supremacy* was the first exhaustive report of its kind in the history of the American military forces. It definitively made the point that the Air Force was the major defense arm of the nation and that defense was clearly dependent on a continuous input of technological and scientific progress.”**

A native Jewish Hungarian born May 11, 1881, Dr. Theodore von Kármán traced his scientific roots through his mother to a great 16th-century mathematician at the imperial court of Prague. According to the doctor, his ancestor created the world’s first mechanical robot, the Golem.

His technical genius was revealed at an early age. By the time he was six years old, he could multiply six-digit numbers in his head with the speed of a calculator. When he was 16 years old he was awarded the Eotvos Prize as the finest mathematics and science student in all of Hungary, and this opened the door for him to begin his outstanding academic, scientific and engineering career.

Despite von Kármán’s scientific roots, his father, a distinguished professor of education at the venerable Pazmany Peter University of Budapest, restricted him from studying math and science.

It wasn’t until he was a teenager that von Kármán returned to the study of math.

He said he could add and subtract in German, English, French and Spanish,

but could only perform multiplication problems in Hungarian.

After starting his career studying fluid mechanics at the Gottingen Mathematical Institute, von Kármán became interested in aeronautics after attending an aerial demonstration. From that point on, he dedicated his life to the science of aeronautics. He moved to Aachen, Germany, to pursue his interest in aerodynamics and was determined to make his mark on aerodynamics research, as director of the Aachen Aeronautical Institute.

For his doctoral dissertation in 1908, von Kármán studied the area of structural mechanics with an emphasis on column buckling, not fluid dynamics for which he is memorialized at AEDC.

In 1915, von Kármán found himself in the middle of World War I and assumed the post of director of research of the Austro-Hungarian Aviation Corps. At this post he began ground-breaking work on helicopters, machine gun and propeller synchronization and fuel tank penetration.

As an Austrian lieutenant during the war, von Kármán watched aerial warfare grow, especially during the last two years of the war.

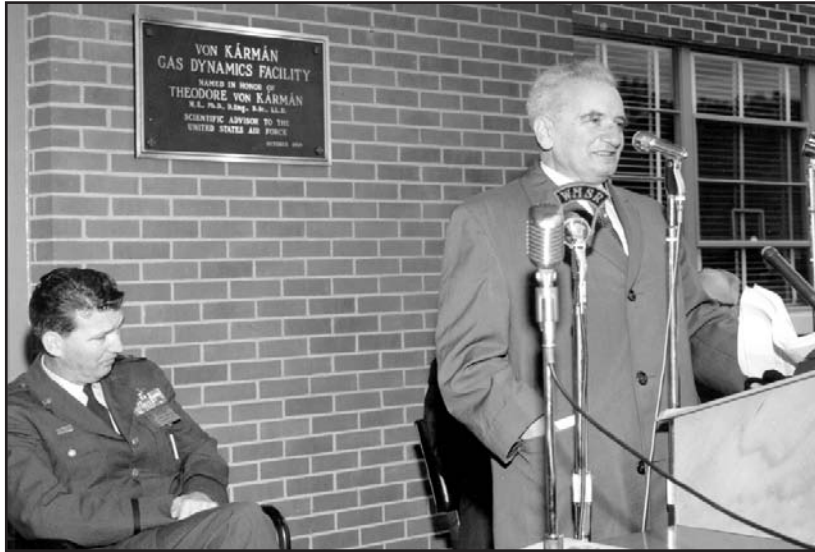
By 1916, he observed planes flying at more than 100 miles per hour carrying machine guns. Photo reconnaissance appeared, and an Italian manufacturer began building heavy bombers while Zeppelin, in Germany, built planes with five engines and 150-foot wingspans.

After returning from the war and resuming his position at the Aachen Aeronautical Institute, von Kármán again focused on aerodynamics research. While he had his eye on his research, the United States, particularly the California Institute



Dr. von Kármán (center, seated) was the first chairman of the Scientific Advisory Group (SAG) that presented General of the Air Force “Hap” Arnold the idea of developing AEDC.

## Dr. Theodore von Kármán



Dr. Theodore von Kármán speaks at the dedication of AEDC's gas dynamics facility being named in his honor. Gen. Bernard Schriever, commander of Air Force Systems Command, listens.

of Technology (Caltech), had their eyes on him.

In the late 1920s, Caltech lured von Kármán to their facilities with a \$4,000 stipend (more than most of their faculty made in an entire year) to act as a consultant for a new wind tunnel they were planning. He dramatically changed the design of the tunnel and over the next several years divided his time between Aachen and Caltech.

By 1930, Caltech had officially added von Kármán to their staff as full-time director of the Guggenheim Aeronautical Laboratory of the California Institute of Technology (GALCIT). While at Caltech, von Kármán's laboratory became regarded as a primary center of interest in the world of aeronautical science. His personal scientific work continued, and he made significant contributions to fluid mechanics, turbulence theory, supersonic flight and mathematics in engineering, as well as aircraft structures and wind erosion of soil.

It was not only his advances in aeronautics, but also his teaching ability that brought him to the notice of General of the Air Force Henry "Hap" Arnold. It was while he was at Caltech that von Kármán developed

a vision of aeronautics similar to the vision Arnold had for the Air Force.

Arnold and von Kármán realized that having a cooperative aeronautics establishment between civilian scientists and military men would have advantages for both sides. They had several meetings where they discussed the future of air research, and while he remained on the staff at Caltech, von Kármán began working with Arnold to improve and advance America's Air Force.

In 1939, Arnold requested that von Kármán design a 20-foot wind tunnel for Wright Field. This was the first facility of its kind – necessary for the Air Corps to make major advances in flight.

Near the end of World War II, Arnold once again called on von Kármán, this time to establish a scientific advisory group to "develop a blueprint for air research for the next 20, 30, perhaps 50 years."

In the spring of 1945, von Kármán and a group of scientists went to Europe to question German scientists and engineers about their rapid progress in aviation during the war. They visited the Bavarian Motor Works (BMW) aircraft engine factory in Munich, the Aerodynamic Laboratory formerly at

Penemunde, and Oetzal, a site in the Tyrolian Alps, where the world's most powerful wind tunnel was then under construction.

In December 1945, von Kármán's group presented their findings in a report they called *Toward New Horizons*, laying out the blueprint for an Air Force Research and development facility. This facility for the study and development of jet propulsion, supersonic aircraft and ballistic missiles, proposed by von Kármán's group, is today the Arnold Engineering Development Center. The von Kármán Institute in Brussels, Belgium, is named in his honor.

In October 1959, AEDC honored von Kármán by renaming the Gas Dynamics Facility after him, marking the first time that the Air Force had named a major facility after a living person. Von Kármán made many other contributions to aerodynamics, including his active involvement in developing supersonic aircraft and intercontinental ballistic missiles.

He developed many theories, such as the effects of forces and currents on aircraft and spacecraft, and co-founded the present NASA Jet Propulsion Laboratory in Pasadena, California. He was also a founder of the Aerojet Corporation.

Von Kármán envisioned the idea of partnership among aeronautical engineers and obtained approval from the North Atlantic Treaty Organization (NATO) to launch the NATO Advisory Group for Aeronautical Research and Development, known by its acronym, AGARD, which he chaired until his death on May 7, 1963.

Von Kármán was the first recipient of the National Medal of Science awarded by President John Kennedy. He was named to the National Aviation Hall of Fame in 1983 for his outstanding contributions to aviation and space technology and received the Presidential Medal of Merit and eight honorary doctorates.

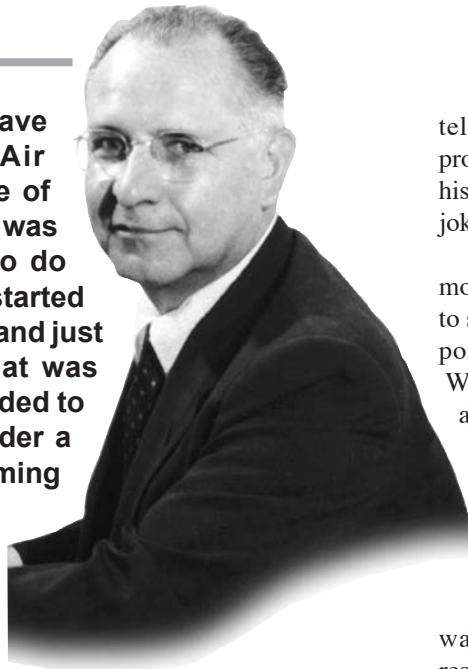
Von Kármán was recognized as an Honorary AEDC Fellow in 2002.

# Dr. Frank Wattendorf

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**“I returned on emergency leave aboard a MATS (Materiel Air Transport Service) plane; one of those old bucket seat C-54s. I was on this plane with nothing to do for a long period of time so I started putting my thoughts together and just started writing them out. That was on June 19, 1945. I recommended to the Air Force that they consider a new center geared to the coming jet age.”**

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Considered one of AEDC’s “founding fathers,” Dr. Frank Wattendorf was born May 23, 1906, in Boston, Massachusetts.

In 1926, he received his bachelor’s degree from Harvard University. As a 20-year-old math major, uninterested in teaching but with a keen interest in aerodynamics, he enrolled in the Massachusetts Institute of Technology’s (MIT) new graduate curriculum in aeronautical engineering. There he met Dr. Theodore von Kármán, at that time, the western world’s leading aerodynamicist, who was a visiting lecturer from the Aachen Institute of Technology, in Germany.

In his book, *The Wind and Beyond*, von Kármán recalls that it was after his opening lecture that a young Wattendorf introduced himself. He told von Kármán that he was interested in his approach to the subject of aerodynamics. He said there was a limited opportunity to learn basic aerodynamic theory in America and asked von Kármán to recommend a school abroad.

Von Kármán recommended Göttingen and Aachen and told him they had no American students at that time.

On a lark, Wattendorf went to the head of MIT’s aeronautics department,

telling him that he had found the professor he wanted to work for on his master’s thesis. Although he said it jokingly, the department head agreed.

Wattendorf, accompanied by his mother, traveled to Aachen in 1927 to study with von Kármán. From that point on, von Kármán considered Wattendorf a member of his family and the young Wattendorf became his most trusted and reliable assistant.

Wattendorf accompanied von Kármán to the California Institute of Technology (Caltech) as his assistant, where Wattendorf was in charge of fluid mechanics research. He also earned his doctorate degree in 1933 from Caltech. Among his contributions to aerodynamics is his work with von Kármán on the 20-foot, 40,000-horsepower wind tunnel at Wright Field in the late 1930s.

During World War II, Wattendorf was appointed a founding member of



**Dr. Wattendorf (right) talks with Arnold Research Organization (ARO) President Bob Williams during a visit to the center in September 1974, on the eve of his departure for Paris, where he was to be awarded the von Kármán Medal, an award presented by NATO’s Advisory Group for Aeronautical Research and Development (AGARD).**

## Dr. Frank Wattendorf

the Scientific Advisory Group (SAG), formed to study America's needs in the aerodynamic field. He was to report on German advances in gas turbine propulsion, wind tunnels and propulsion facilities.

In 1945, while detailed to postwar Germany to study its advancements in aeronautical and aerodynamic research, Wattendorf was notified of his father's death. He crossed the Atlantic in a combat-painted C-54 transport plane, where he poured through highly-classified notes and papers that lead him to pen the now famous *Trans-Atlantic Memo* to Brig. Gen. Franklin O. Carroll, chief of the Army Air Forces Engineering Division at Wright Field, Ohio, and later AEDC's first commander.

"I returned on emergency leave aboard a MATS (Materiel Air Transport Service) plane; one of those old bucket seat C-54s," Wattendorf said. "I was on this plane with nothing to do for a long period of time so I started putting my thoughts together and just started writing them out. That was on June 19, 1945. I recommended to the Air Force that they consider a new center geared to the coming jet age."

His memo became the first recommendation for AEDC, stating the need for facilities to develop and test supersonic aircraft and missiles. It later became a large part of von Kármán's *Toward New Horizons*, the blueprint for Air Force research and development.

Wattendorf was appointed civilian chairman of the AEDC Planning Group and was awarded the Medal of Freedom in 1946 for his overseas surveys and his recommendation for the new testing complex. Among his recommendations was shipping parts of large German facilities to the U.S. for eventual use in the new test center.

Approval was quickly and easily obtained through the Allied Command in Europe; shipping began in 1945. He was a founding member of the NATO Advisory



Gen. Carroll, R. M. Williams, Dr. Wattendorf, Gen. Schriever and Gen. Gossick pause in front of the supersonic wind tunnel during a tour in 1965.



General Carl Spaatz, Chief of Staff of the Air Force, presents Dr. Frank Wattendorf an award while Dr. Theodore von Kármán (center) looks on.

Group for Aeronautical Research and Development (AGARD), the von Kármán Institute for Fluid Dynamics, and the International Council for the Aeronautical Sciences. Dr. Wattendorf retired in 1968 and was awarded the U. S. Air Force (USAF) Medal for Exceptional Civilian Service.

For nearly 15 years, he assisted in the strategic planning and development of new test facilities and in the improvement of existing facilities.

In 1980, the American Institute of

Aeronautics and Astronautics (AIAA) presented him with the Ground Testing Award for achievements in the development and operation of advanced aerodynamic and propulsion test facilities.

Frank Wattendorf died in 1986.

In 1987, his widow, Glenn, and son, Roger, attended ceremonies that named the base access highway in his memory.

In 2006, Wattendorf was recognized for his contributions to the center as an Honorary AEDC Fellow.

# Gen. Bernard A. Schriever



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**“There’s no question, his [Arnold’s] greatness was that he created the infrastructure. He visualized the kind of infrastructure that the Air Force needed to really get into the technology age.”**

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In his role as the father of the Intercontinental Ballistic Missile (ICBM) program, General Bernard Adolph Schriever relied heavily on AEDC for crucial aerodynamic and rocket propulsion data.

A frequent visitor to the center, he also worked with AEDC Fellow Dr. Bernhard Goethert to form the University of Tennessee Space Institute (UTSI).

Schriever was born in Bremen, Germany, in 1910, the son of an engineering officer on a German ship line. He came to America in 1917, when his parents emigrated from Germany. He became a naturalized citizen in 1923 and graduated from Texas A&M in 1931 with a bachelor of science degree.

He was commissioned in the Field Artillery, but in July 1932 began flight training at Randolph Field, Texas, and earned his wings in June 1933.

Schriever went to Panama for duty at Albrook Field and in September 1937 left the Air Corps to fly as a pilot with Northwest Airlines. He returned to duty in October 1938 with the 7th Bomb group at Hamilton and a year

later became a test pilot at Wright Field, Ohio, where he also attended the Air Corps Engineering School, graduating in July 1941.

He then took an advanced course in aeronautical engineering at Stanford University, was promoted to captain in April 1942, and earned his master’s

degree in June as a newly promoted major.

In January 1943, Schriever moved to the 5th Air Force Service Command in maintenance and engineering assignments, as a chief of staff, finally becoming commanding officer of advance headquarters for the Far East Air Service Command.

He was promoted to lieutenant colonel in August 1943 and to colonel that December.

After the war, Colonel Schriever’s old boss, General Arnold, made him the chief of scientific liaison for the Air Force Deputy Chief of Staff-Materiel. General Schriever later wrote in the book *The U.S. Air Force in Space* that General Arnold made the move because many of the scientists that helped make the huge technological breakthroughs achieved during the war were returning to their civilian jobs at universities and yet “we need to maintain a close and cooperative relationship with the scientific



Seventeen “stars” closely associated with the history of Arnold Center, (left to right) Lt. Gen. Don. Putt, Maj. Gen. Franklin Carroll, Gen. Bernard Schriever, Brig. Gen. Lee Gossick, Maj. Gen. Leif Sverdrup, Lt. Gen. Lawrence Craigie and Maj. Gen. Edward Powers.



## General Bernard Schriever

community. It is not enough to just have a close relationship with the aviation industry.”

In his new job, Colonel Schriever worked with several of the scientists whose research formed the foundation of today’s space programs, including the famous Dr. Theodore von Kármán, who had been asked by General Arnold to form the Air Force Scientific Advisory Group (SAG).

Colonel Schriever worked with the SAG, ensuring that they understood the goals of the nation’s leadership, and ensuring that the government, in turn, gave the board what it needed.

Schriever graduated from the National War College in June 1950 and returned to Headquarters Air Force as assistant for evaluation in development.

He was promoted to brigadier general in June 1953.

Schriever was assigned to the Pentagon, where he later recounted the interest of military and civilian leaders concerning the feasibility of reconnaissance satellites, especially as the nuclear age began.

“Pearl Harbor had really given us a shock, especially because of the amount of damage inflicted by that surprise attack,” Schriever said during a 1998 interview.

“President Eisenhower wanted us to determine how we could best get strategic intelligence to avoid a nuclear Pearl Harbor. That was the deciding issue in putting the Air Force into the space business.”

Space took center stage on Oct. 4, 1957, when the Soviet Union launched the *Sputnik* satellite. The Air Force responded by sending *Discovery One* into orbit on Feb. 28, 1959.

The race to space included many successes and failures for both the ICBM and satellite programs. But Schriever said that he and his group accepted that they were taking risks because they knew that if they did not develop a long-range ICBM capability and satellite reconnaissance system, there would be a major

instability in the strategic balance between the U.S. and the Soviet Union.

Schriever began his long association with Air Force Research and Development Command – later Air Force Systems Command – in June 1954 as assistant to the commander. The next month he headed a small group of officers who went to Los Angeles to organize and form what later became the Air Force’s ballistic and systems division under Air Force Systems Command (which later became the Space and Missile Systems Center [SMC] under Air Force Material Command [AFMC]).

The end products were ballistic missiles such as Thor, Atlas, Titan and Minuteman and all of the aerospace systems that have been launched into orbit, including support for NASA’s man-in-space programs. Schriever was promoted to two-star rank in December 1955, lieutenant general on April 25, 1959, and to full general on July 1, 1961. In April 1957, his picture appeared on the cover of *Time* magazine, which called him “America’s Missileman.”

Schriever retired in 1966, although



Considered the father of the Air Force’s ballistic missile and space programs, Gen. Schriever addressed America’s need for space superiority during the inaugural Air Force Office of Scientific Research and Astronautics Symposium in 1957.

he continued to act as an adviser for various corporate and government clients. In honor of his service, Schriever Air Force Base in Colorado Springs, Colorado, was named for him in 1998.

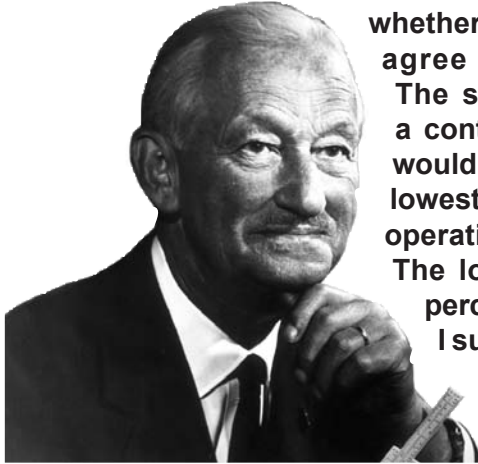
Schriever was recognized as an Honorary AEDC Fellow in 2004 for his pioneering efforts in shaping the Air Force and AEDC.

General Schriever passed away June 20, 2005, at the age of 94.



Gen. Schriever addresses the first convocation of the University of Tennessee Space Institute (UTSI).

# Maj. Gen. Leif Sverdrup



**“The secretary of the Air Force [Symington] called me to his office and asked whether our organization would agree to operate the center. The secretary advised that if a contract were made, the fee would have to be lower than the lowest then in effect for civilian operation of a military agency. The lowest fee then was four percent of the estimated cost. I suggested that we might be able to take it on for three and a half percent.”**

Leif Sverdrup once wrote in his column “Old Man’s Corner,” in his company’s newsletter, SPICE, that “it is not only old soldiers who never die. I believe engineers, more so, are in that category, for their monuments remain long after they are gone.”

Today, more than 30 years after his death, the bridges and structures designed and constructed by Sverdrup and his firm stand as testaments to his engineering abilities.

Difficult to pronounce and almost as hard to spell, few names in the engineering world carry as much respect and clout as “Sverdrup.” His legacy includes the 17-mile-long Chesapeake Bay Bridge-Tunnel, named one of the “Seven Engineering Wonders of the Modern World” after its completion in 1964, the Bhumiphol Dam in Thailand and St. Louis’ Busch Memorial Stadium, built in the late 1960s.

But it was one particular project – designing a complex of wind tunnels and other testing facilities at a new site for the Air Force – first discussed with him in 1946 – that would firmly establish his company in this area.

Leif Johan Sverdrup was born on Ytre Sulen in Norway on Jan. 11, 1898. Sverdrup, the son of a minister, first showed an interest in science when he was about 13, conducting experiments on a chemistry set in his parents’ basement.

At 16, Sverdrup boarded the *Kristianiafjord* and left Norway for America. Arriving in New York on Dec. 7, 1914, young Sverdrup took a train to his Uncle George’s home in Minneapolis, Minnesota. Two years later, he had earned enough money to begin classes at Augsburg College in Minneapolis. He graduated in May 1918 with a Bachelor of Arts degree, and later that summer, enlisted as a private in the U.S. Army.

During this period, the five-year residency requirement was waived for members of the armed forces, so on Sept. 30, 1918, he took an oath of allegiance and became a U.S. citizen. While in basic training, he received his certificate of naturalization.

Eventually he gave up trying to teach people to pronounce his first name correctly – “Lafe” instead of “Leaf,” and asked his friends to

introduce him as Jack Sverdrup.

In 1919, Sverdrup obtained a commission as a second lieutenant in the Field Artillery, but then opted to go into the inactive reserves, where he served two, five-year terms. In 1929, he was honorably discharged.

Meanwhile, in 1919, he had decided to become an engineer and enrolled at the University of Minnesota. It was here that he first met Professor John Ira Parcel, his indeterminate structures professor, who would later become his business partner.

After graduation from the University of Minnesota in 1921 with a Bachelor of Science degree in civil engineering, Sverdrup took the first job he was offered – bridge inspector with the Minnesota State Highway Department. He spent a year in that job before moving to the Missouri State Highway Department. But it would be a bridge in Hermann that would prove the catalyst to propel a young Sverdrup into business success when, in 1927, he was selected to design a bridge over the Missouri



**Sverdrup at AEDC in 1955 at the center’s PWT construction site.**



**ARO President Leif “Jack” Sverdrup cuts the cake celebrating ARO’s 10th anniversary with a sabre borrowed for the event.**

River. Leaving the Missouri State Highway Department, Sverdrup started out on his own. However, he quickly realized that he needed a partner.

“I didn’t want to be alone,” Sverdrup said. “I wanted a partner who was older than myself. Since I was not known in the technical world, John Parcel came to mind at once. I went to see him and he agreed to come with me.”

Sverdrup & Parcel was officially founded on April 1, 1928, as a civil engineering firm specializing in the field of bridges. In October 1941, at the Army’s request, Sverdrup took on a job that his firm had previously declined – developing airfields in the Pacific so American bombers could be flown to Gen. Douglas MacArthur for the defense of the Philippines. He then signed a contract to plan and design all the work in the Fiji Islands, New Caledonia, New Hebrides and the Solomons.

Two days after the attack on Pearl Harbor, MacArthur sent a message that he wanted Sverdrup & Parcel to

handle all of his engineering work.

During this period, Sverdrup relinquished all connections with his firm – no profits, salary or business communications. Three years later, in 1945, he was a major general, commander of all engineering forces in the southwest Pacific, chief engineer to MacArthur and a national hero of the engineering fraternity.

During his absence, Sverdrup & Parcel had entered the age of advanced technology by developing wind tunnels at Wright Field in Dayton, Ohio. In 1946, Sverdrup & Parcel was presented with the possibility of designing a complex of wind tunnels and other testing facilities at a site for the Air Force. The project was the Air Engineering Development Center.

Although the details of the job were staggering and Sverdrup & Parcel was a 50-man organization, Sverdrup felt the firm could meet the challenge, but he left the decision to his partners. On April 22, 1950, the Arnold Research Organization – or ARO – was incorporated solely for the purpose of managing, maintaining and

operating the new center.

*Time* magazine, in a story in its Aug. 7, 1950, issue titled “A Norseman Named Leif,” wrote:

“Last week the Air Force called Sverdrup to a bigger job. To ARO, Inc., a Sverdrup & Parcel subsidiary, it has the task of operating its \$100 million Arnold Engineering Development Center, now a building at Tullahoma, Tenn. That was fitting enough; Sverdrup’s firm drew the plant’s blueprints five years ago.

“At the Tullahoma center, which will not be in complete operation until 1952, Sverdrup’s men will test life-size mock-ups of jets, turbojets and rockets under conditions simulating altitudes up to 75,000 ft. They will simulate conditions found at sea-level speeds up to 7,500 m.p.h. To Sverdrup thus went one of the key jobs in keeping the U.S. ahead in the race for technical supremacy.”

MacArthur called Sverdrup an “engineer soldier at his best” when he pinned the Distinguished Service Cross on him in 1945. Sverdrup was also awarded the Distinguished Service Medal, the Silver Star, the Legion of Merit and the Purple Heart. He won military citations and medals from England, Australia and other lands, including Norway’s esteemed Order of St. Olaf. After the war, he reactivated the 102nd (Ozark) Division of the U.S. Army Reserve.

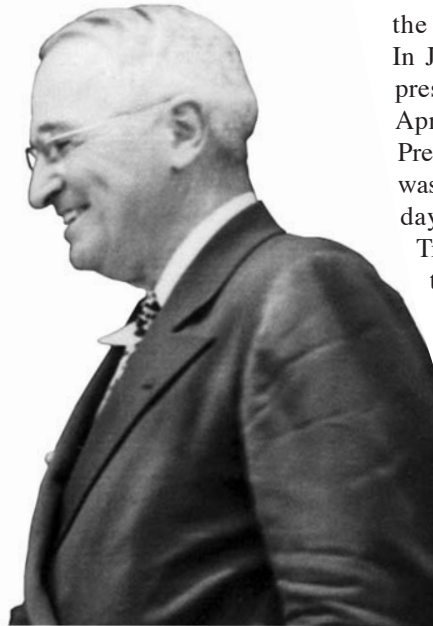
For his service as Commanding General of the Division from 1947 to 1958, the Army added an Oak Leaf Cluster to his Distinguished Service Medal. Sverdrup was one of St. Louis’ best-known civic leaders. He headed fund drives for the Boy Scouts, the United Fund and the Arts and Education Council. He also served three terms on the Board of Visitors of the U.S. Military Academy at West Point.

Sverdrup died in 1976 after becoming ill during a duck hunt. He was buried with full military honors in Valhalla Cemetery in Hanley Hills, Missouri.

# President Harry S Truman



**“It is most appropriate that this center for pioneering in the science of flight should bear the name General Henry H. Arnold. ‘Hap’ Arnold was a great pioneer in the development of our Air Force... He knew that you can’t have a first-class Air Force with second-class aircraft.”**



Harry S Truman was born in Lamar, Missouri, and was raised in Independence. In 1901, he graduated from high school and worked briefly as a timekeeper for a railroad construction contractor and then as a clerk at two Kansas City banks.

In 1906, he moved to Grandview, where he assisted his father on the family’s farm. Truman was a successful farmer for more than a decade and he served in the Missouri National Guard from 1905 to 1911.

At the beginning of World War I, he helped organize the 2nd Regiment of Missouri Field Artillery, later called into federal service as the 129th Field Artillery and deployed to France, where Truman was promoted to captain and saw combat.

After the war, he opened a men’s clothing store in Kansas City that failed. He narrowly escaped bankruptcy in the post-war recession years, but managed to pay off his share of the store’s debt.

Truman’s political career began in 1922 when he was elected one of three judges of the Jackson County Court. Truman’s duties were more

administrative than judicial. Although his re-election bid was unsuccessful, in 1926, he won election as presiding judge in the Jackson County Court. His next re-election bid, in 1930, was a success. In 1934, Truman was elected to the U.S. Senate, where he played a key role in passing the Civil Aeronautics Act of 1938 and the Transportation Act of 1940.

After re-election in 1940, he gained national attention as the chairman of the Senate Special Committee to Investigate the National Defense Program.

This committee, called The Truman Committee, successfully ensured that defense contractors delivered quality goods to the nation at fair prices.

In July 1944, Truman received

the vice-presidential nomination. In January 1945, he took the vice-presidential oath of office, and on April 12, 1945, after the death of President Franklin D. Roosevelt, he was sworn in as president. In the early days of his presidency, President Truman was faced with the decision to drop atomic bombs on Japan. Also, during that first year, he saw the founding of the United Nations and the growth of a confrontational Soviet Union. Important foreign policy initiatives marked his term. His desire was to prevent the expansion and influence of the Soviet Union. The Truman Doctrine provided military aid to countries resisting communism while the North

Atlantic Treaty Organization (NATO) provided a military barrier confronting the Soviet-dominated portion of Europe.

On the home front, Truman issued executive orders desegregating the armed forces and forbidding racial discrimination in federal employment.



**The moment of Dedication at the Arnold Engineering Development Center came on June 25, 1951, when President Harry Truman pulled a cord to draw aside the curtain revealing the dedicatory plaque mounted on a large granite rock. Mrs. Henry Arnold, widow of General of the Air Force H. H. “Hap” Arnold, looks on. The event took place on the 65th anniversary of the General’s birth.**



# **Appendix 5**

## **President Harry S Truman's AEDC Dedication Speech**

# President Harry S Truman's AEDC Dedication Speech



President Harry S Truman gave the dedication speech at the AEDC June 25, 1951.

“I am glad to be here in Tennessee to dedicate this great aviation development center. The great industrial progress of Tennessee, and of the whole South, makes it possible to build this key defense installation in this area. I am sure that the presence of this Center here will contribute further to the growth and prosperity of this region.

“It is most appropriate that this center for pioneering in the science of flight should bear the name General Henry H. Arnold. “Hap” Arnold was a great pioneer in the development of our Air Force.

“He was one of the first three officers in our Armed Forces to learn to fly a plane. He won his first flying trophy in a Wright biplane that had a 40-horsepower engine turning two propellers by the chain-and-sprocket method—the same kind of power transmission a bicycle has.

“General Arnold lived to command a mighty Air Force of eighty-thousand planes. Instead of 40 horsepower, some of the planes in that air force had 10,000 horsepower. And the power transmission system of some of those planes was more like a skyrocket than a bicycle.



President Harry S Truman pulls a cord to draw aside the curtain, revealing the dedicatory plaque mounted on a large granite rock. Mrs. Henry Arnold, widow of General of the Air Force H. H. “Hap” Arnold, looks on.

“General Arnold had a lot to do with those improvements. He knew that you can’t have a first-class Air Force with second-class aircraft. He would have been delighted with the air-research center, which will do so much to make further improvements possible.

“I am happy to dedicate this center to his memory and to name it the ‘Arnold Engineering Development Center.’

“The scientists who work here will explore what lies on the other side of the speed of sound. This is part of our effort to make our air power the best in the world—and to keep it the best in the world. This applies to the planes of the Air Force, the Navy, and our Marines. It applies to our guided missiles and all the future developments that science may bring.

“The purpose of our air power is to help keep the peace of the world. This is our fundamental objective. A large and powerful air force is one of the essential weapons we must have to help prevent aggression – or to crush aggression if it is launched.

“We need many other weapons as well – military, economic and psychological weapons – if we are to prevent a third world war. And we must keep finding new and better methods in each of these fields, just as we must keep developing faster and more powerful planes.

“We must use every possible means of securing and maintaining the peace. Our whole policy is based on world peace. That has been our policy all along, and it is still our policy. This hasn’t changed one bit.

“Since World War II, we have done our utmost to build an international organization to keep peace in the world. We have done that in the interest of the United States,

because the only sure way to keep our own country safe and secure is to have world peace. The United Nations is the most far-reaching attempt that man has ever made to protect himself against the scourge of war.

“But the rulers of the Soviet Union had a different idea. They did not want to cooperate in keeping the peace. The people of Russia (the common everyday people of Russia) want peace just as much as anyone else, but their rulers in the Kremlin saw that the nations of the world had been weakened and demoralized by the agonies of the war. They saw a chance to move in and impose their own system of slavery on other nations.

“We tried to settle postwar problems with the Soviet Union on a decent and honorable basis, but they broke one agreement after another. We offered to place the means of atomic warfare under effective international control. That was an offer to save mankind forever from the horror of the atomic war. But the Soviet Union refused to accept it.

“Our actions showed that we were for peace. Even though our efforts were rejected by the Soviet rulers, our actions won for us the confidence and trust of other free nations. In spite of all the false and lying propaganda of the Kremlin, it was clear to all the world that we wanted peace.

“At the same time, we made it clear to all the world that we would not engage in appeasement. When the Soviet Union began its campaign of undermining and destroying other free nations, we did not sit idly by.

“We came to the aid of Greece and Turkey when they stood in danger of being taken over by communist aggression in 1947. As a result, these countries today are free and strong and independent.

“We came to the aid of the peoples of France and Italy in their struggle against the political onslaught of Communism. In each of these countries, Communism has been defeated in two free elections since 1947. There is no longer any danger that they will vote themselves into the hands of the Soviet Union.

“We came to the aid of the brave people of Berlin when the Kremlin tried to take them over. We and our allies kept Berlin alive by the airlift, and it is still free today.

“We came to the aid of China when it was threatened by Communist civil war. We put billions of dollars’ worth of arms and supplies into China to aid the Chinese Nationalist government. We gave them more help than we gave Greece or Italy or Berlin. The government of Greece took our aid and fought for freedom. But many of the generals of National China took our aid and surrendered.

“We can investigate the situation in China from now until doomsday, but the facts will always remain the same: China was taken over by the Communists because of the failure of the Nationalist Government to mobilize the strength of China to maintain its freedom.

“After all, our aid can be effective only when the people help themselves. We are continuing to give aid to

the Chinese Nationalists on Formosa, and that aid will be effective if they are now willing to do their part.

“On June 25, 1950, one year ago today, the Communist rulers resorted to an outright war. They sent Communist armies on a mission of conquest against a small and peaceful country. The act struck at the very life of the United Nations. It struck at all our hopes of peace.

“There was only one thing to do in that situation – and we did it. If we had given in – if we had let the Republic of Korea go under – no nation in the world would have felt safe. The whole idea of a world organization of nations took collective military action to halt aggression. And, acting together, we halted it.

“A year ago today, Korea looked like an easy conquest to the Soviet rulers in Moscow and their agents in the Far East. But they were wrong. Today, after more than a million Communist casualties – after the destruction of one Communist army after another – the forces of aggression have been thrown back on their heels. They are back behind the line where they started.

“Things have not turned out the way the Communists expected.

“The United Nations has not been shattered. Instead, it is stronger today than it was a year ago.

“We have been fighting this conflict in Korea to prevent a Third World War. So far, we have succeeded. We have blocked aggression. And we have kept the conflict from spreading.

“Men from the United States and from many other free countries have fought together in Korea. They have fought bravely, heroically, often against overwhelming odds. Many have given their lives. No men ever did more for their country or for peace and freedom in the world than those men who fought in Korea.

“The attack on Korea has stimulated the free nations to build up their defenses in dead earnest. Korea convinced the free nations that they had to have armies and equipment ready to defend themselves.

“The United States is leading the way, with defense expenditures of 40 billion dollars. Other nations are devoting a large share of their national effort to our mutual defense.

“Never before in history have we taken such measures to keep the peace. Never have the odds against an aggressor been made so clear before the attack was launched.

“The Kaiser, and Hitler, when they started their great wars of aggression, believed that the United States would not come in. They counted on being able to divide the free nations and pick them off one at a time. There could be no excuse for making that mistake today.

“We have the United Nations – which expresses the conscience and the collective will of the free world.

“We have the Organization of American States – which is building the strength of this hemisphere.

## AEDC Dedication Speech

“We have the North Atlantic Treaty – which commits all the nations of the Atlantic community to fight together against aggression.

“We have unified land, sea, and air forces in Europe, under the command of General Eisenhower.

“We are strengthening the free nations of the Far East and setting up collective security arrangements in the Pacific.

“We are building up our defenses and the defenses of other free nations rapidly and effectively.

“Most important of all, we have shown that we will fight to resist aggression. The free nations are fighting – and winning – in Korea.

“Never before has an aggressor been confronted with such a series of positive measures to keep the peace. Never before in history have there been such deterrents to the outbreak of world war.

“Of course, we cannot promise that there will not be a world war. The Kremlin has it in its power to bring about such a war if it desires. It has a powerful military machine, and its rulers are absolute tyrants.

“We cannot be sure what the Soviet rulers will do.

“But we can put ourselves in a position to say to them: Attack – and you will have the united resources of the free nations thrown against you; attack – and you will be confronted by a war you cannot possibly win.

“If we could have said that to the Kaiser, or to Hitler, or to Tojo, the history of the world would have been very different.

“It hasn’t been easy – but it is a record of tremendous progress in man’s age-old struggle for peace and security.

“We have made great progress, but we are not yet out of danger. The Kremlin is still trying to divide the free nations. The thing that the Kremlin fears most is the unit of the free world.

“The rulers of the Soviet Union have been trying to split up the nations of the North Atlantic Treaty. They have been trying to sow distrust between us and other free countries. Their great objective is to strip us of our allies – to force us to ‘go it alone.’

“If they could do that, they could go ahead with their plan of taking over the world, nation by nation.

“Unfortunately, it isn’t only the Kremlin that has been trying to separate us from our allies. There are some people in this country, too, who have been trying to get us to ‘go it alone.’ There are people here who have been sowing distrust of our allies and magnifying our differences with them. Some of these people are sincere but misguided. Others are deliberately putting politics ahead of their country’s safety. Now, I have no objection to honest political debate. That’s the way things get decided in this country.

“But some of the people who are trying to get us to ‘go it alone’ aren’t engaging in honest political debate. They

know they couldn’t win that way. So they have launched a campaign to destroy the trust and confidence of the people in their government.

“They are trying to set the people against the government, by spreading fear and slander and outright lies. They have attacked the integrity of the Joint Chiefs of Staff. They have maliciously attacked General Bradley, who is one of the greatest soldiers this country has ever produced. They have tried to besmirch the loyalty of General Marshall, who directed our strategy in winning the greatest war in history. They have deliberately tried to destroy Dean Acheson – one of the greatest secretaries of state in the history of this country.

“The political smear campaign is doing this country no good. It’s playing right into the hands of the Russians.

“Lies, slander, mud slinging are the weapons of the totalitarians. No man of morals or ethics will use them.

“As far as I am concerned, there ought to be no Democrats and no Republicans in the field of foreign policy. We are all American, all citizens of the same great republic. We have had a bipartisan foreign policy in this country since Pearl Harbor. I would like to keep it that way. I know a great many Republicans who want to keep it that way, too.

“I say to them – this is the time, now, to show the real loyalty of the Republican party to the great ideals on which this country is founded. Now is the time to put a stop to the sordid efforts to make political gains by stirring up fear and distrust about our foreign policy. Now is the time to say to the dividers and confusers: No political party ever got anywhere in the long run by playing fast and loose with the security of the nation in time of great peril.

“Partisan efforts to label our foreign policy as ‘appeasement’ – to tag it as a policy of ‘fear’ or ‘timidity’ – point to only one thing. They point to our ‘going it alone,’ down the road to World War III.

“Is it a policy of fear to bring the free nations of the world together in a great unified movement to maintain peace? Is it a policy of timidity to come to the aid of the Greeks and the Turks and the other free people who are fighting back against the Communist threat? Is it policy of appeasement to fight armed aggression and hurl it back in Korea? Of course it’s not. Anybody with any common sense knows it’s not.

“And look at the alternatives these critics have to present. Here is what they say. Take a chance on spreading the conflict in Korea. Take a chance on tying up all our resources in a vast war in Asia. Take a chance on losing our allies in Europe. Take a chance the Soviet Union won’t fight in the Far East. Take a chance we won’t have a Third World War.

“They want us to play Russian roulette with the foreign policy of the United States – and with all the chambers of the pistol loaded.



“That’s the kind of wisdom and thinking that has been coming out of the dividers and confusers in the last few months.

“That is not a policy. That is not the way to defend this country and the cause of world peace in these dangerous times. No President who has any sense of the responsibility for the welfare of this great country is going to meet the grave issues of war and peace on such a foolish basis as that.

“I am glad that we have had the recent hearing in the Senate on our foreign policy. These hearings have been thorough and have been conducted fairly. They have done a great deal to explain to our people the situation the world is in, and the way we are meeting it. They have demonstrated, again, that we are on the right course.

“But the important problem right now is not the past; it is the future. The world will not stand still while we examine the whole course of our foreign policy since 1941.

“Our military buildup, our economic strength at home, ... They are essential to our program of peace.

“We are right in the middle of a great effort to build up our defenses and to check aggression. We can’t go on with this effort unless the Congress enacts certain basic legislation.

“Every group in the country has a vital part to play in our great effort for peace. The part of the Congress is to give the country the legislation we need to go forward. Without that, none of the rest of us can do our job.

“We must have effective laws to curb inflation and to boost defense production.

“We must have the appropriations needed to build up our defense forces.

“We must have legislation to enable us to continue our policy of military and economic aid to our allies.

“To make our nation safe, we must have strong allies. We cannot have them unless we help the other free countries to defend themselves. Time is too short, and the danger too pressing to wait for these war-weakened countries to build up their own defenses without help from us. This aid is vital to our plans for defense, to our national security, to our hopes for peace.

“Let me show you just how essential it is. We all know that our Air Force is very important. But did you ever stop

to think how much its effectiveness depends on our allies?

“The Air Force has to have bases overseas to be in the right place to give full protection to our own country, as well as our allies. This is a clear example of how joining with other free countries for mutual defense helps all of us.

“Our allies cannot maintain and defend the necessary bases unless we give them aid. Giving aid to our allies is just as necessary as building airplanes if we are to have world peace.

“Our military buildup, our development of weapons, our economic strength at home, our foreign aid programs, our efforts in the United Nations are all parts of a whole. They are all essential to our program of peace.

“There is no one weapon – no single service – no particular military or diplomatic device – that can save us by itself. All our efforts are needed.

“We now have a program that is using all these elements of our national policy for the great purpose of peace. We are improving it as we go along. We are getting good results.

“We must get on with the job.

“We must build up our strength, but we must always keep the door open to the peaceful settlement of differences.

“We are ready to join in a peaceful settlement in Korea now as we have always been, but it must be a real settlement which fully ends the aggression and restores peace and security to the area and to the gallant South Korean people.

“In Korea and in the rest of the world we must be ready to take any steps which truly advance us toward world peace. But we must avoid like the plague rash actions which would take unnecessary risks of world war or weak actions which would reward aggression.

“We must be firm and consistent and level headed. If we get discouraged or impatient, we can lose everything we are working for. If we carry on with faith and courage, we can succeed.

“And if we succeed, we will have marked one of the most important turning points in the history of man. We will have established a firm peace for the whole world to last for years to come.

“That is a goal to challenge the best that is in us. Let us move toward it resolutely with faith in God and with confidence in ourselves.”



# **Appendix 6**

## **Facilities Capabilities Charts**

# Facilities Capabilities

Engine Test Facilities Capabilities						
Propulsion Development Test Cell	Test Section Size		Nominal Capability Range			
	Cross Section (ft)	Length (ft)	Total Temperature (°F)	Speed Range	Pressure Altitude (Nominal, ft)	Axial Thrust Capacity (lb)
Test Cell C-1	28 diam	45	-60 - 350	Mach 0 - 2.3	Sea Level - 75,000	100,000
Test Cell C-2	28 diam	47	-40 - 350	Mach 0 - 2.3	Sea Level - 75,000	100,000
Test Cell J-1	16 diam	44	-60 - 720	Mach 0 - 3.2	Sea Level - 75,000	70,000
Test Cell J-2	20 diam	46	-60 - 450	Mach 0 - 2.6	Sea Level - 75,000	50,000
Test Cell SL-2	24 x 24	60	20 - 270	Mach 0 - 1.2	Sea Level	70,000
Test Cell SL-3	24 x 24	60	20 - 270	Mach 0 - 1.2	Sea Level	70,000
Test Cell T-3	12 diam	15	-85 - 1,200	Mach 0 - 4.0	Sea Level - 100,000	20,000
Test Cell T-4	12 diam	47	-40 - 400	Mach 0 - 2.5	Sea Level - 75,000	50,000
Test Cell T-11	10 x 10	17	-80 - 250	Mach 0 - 2.0	Sea Level - 55,000	30,000

NOTE 1: Expanded capability is available with custom upgrades to test cells.  
 NOTE 2: Maximum performance values (temperature, speed and altitude) do not occur simultaneously. Comparison of specific test points to cell capability will be required to ascertain feasibility.

Wind Tunnel Test Facilities Capabilities								
Tunnel	Test Section Size		Speed Range (Mach No.)	Reynolds No. Range (million per ft)	Dynamic Pressure (psf)	Total Pressure	Total Temperature (° F)	Pressure Altitude (nominal, K ft)
	Cross Section (ft)	Length*						
Propulsion Wind Tunnel 16T	16 x 16	40	0.05 - 1.6	0.03 - 7.3	0.35 - 1,150	200 - 3,950 (psf)	80 - 140	Sea Level - 76
Propulsion Wind Tunnel 16S†	16 x 16	40	1.5 - 4.75	0.1 - 2.4	25 - 550	200 - 1,900 (psf)	120 - 580	45 - 155
Aerodynamic Wind Tunnel 4T	4 x 4	12.5	0.05 - 2.46	2.0 - 7.1	0.35 - 1,450	200 - 3,400 (psf)	80 - 140	Sea Level - 98
Supersonic Wind Tunnel A	3.3 x 3.3	9.0	1.5 - 5.5	0.3 - 9.2	53 - 1,780	1.5 - 200 (psi)	70 - 290	16 - 151
Hypersonic Wind Tunnel B	4.17 diam	9.0	6 or 8	0.3 - 4.7	43 - 590	20 - 900 (psi)	240 - 890	98 - 180
Hypersonic Wind Tunnel C	4.17 diam	9.0	10	0.3 - 2.4	43 - 430	200 - 1,900 (psi)	1,190 - 1,490	132 - 188
Hypervelocity Wind Tunnel 9 (Hypersonic)	2.9 diam free jet	9	8	4 - 48	960 - 11,300	1,000 - 12,500 (psi)	1,100 - 1,200	Sea Level - 65
	5 diam	12	10	0.5 - 20	95 - 4,000	300 - 14,000 (psi)	1,200 - 1,350	39 - 111
	5 diam	12	14	0.055 - 3.6	8 - 900	100 - 19,000	1,750 - 2,800	82 - 173
Aerothermal Wind Tunnel C	2.08 diam free jet	3.0	8	0.7 - 7.8	132 - 1,322	200 - 1,900 (psi)	760 - 1,440	95 - 149
	2.08 diam free jet	3.0	4	0.2 - 8.1	231 - 1,928	20 - 180 (psi)	2,600 - 1,200	56 - 105
Hypervelocity Wind Tunnel 9 (Aerothermal)**	11.3 (in) diam free jet	6	6.7	4 - 7.6	3,540 - 6,850	2,600 - 5,500	2,100 - 2,900	52 - 67
National Full-Scale Aerodynamics Complex**	40 x 80	80	0 - 300 knots	<3	0 - 262			Sea Level
	80 x 120	190	0 - 100 knots	<1.1	0 - 34			Sea Level

\* Nominal test section length dimensions are shown. The actual model lengths that can be tested depend on Mach number and should be coordinated with the AEDC test engineering staff.  
 † Inactive  
 \*\* Geographically separated locations

Space and Missile Test Facilities Capabilities								
<b>Lethality</b>	<b>Facility</b>	<b>Projectile Size (in. diam)</b>	<b>Launch Velocity (ft/sec)</b>	<b>Projectile Mass (lbs)</b>	<b>Pressure Altitude (ft)</b>	<b>Run Time (shot/day)</b>		
Ballistic Ranges - Hypervelocity and Impact Guns	Range G	3.3	4900 - 23,000	1.1 - 13.2	Sea Level - 225,000	1		
	Range G	4.0	4900 - 19,700	1.1 - 13.2	Sea Level - 225,000	1		
	Range G	8.0	5600 - 17,100	13.2 - 44.1	Sea Level - 225,000	1		
	Range I	2.5	4900 - 21,300	0.7 - 8.8	Sea Level - 225,000	1		
	Range S1	0.3 - 0.75	4900 - 26,200	0.018 - 0.036 (oz)	Sea Level - 225,000	2		
Range S3	7.0	131 - 2,300	3.3 - 55.1	Sea Level	2			
<b>Rocket Propulsion</b>	<b>Facility</b>	<b>Test Section Size</b>	<b>Thrust Stand (lb)</b>	<b>Pressure Altitude (ft)</b>	<b>Cell Temp Control (°F)</b>	<b>Run Time (min)</b>		
Solid Propellant	Cell J-6	26 ft diam x 62 ft long	5,000 - 500,000	up to 100,000	15 - 110	1 - 6 min		
Liquid Propellant	Cell J-4†	48 ft diam x 82 ft high	5,000 - 500,000	up to 100,000		5 min		
<b>Aerothermal</b>	<b>Facility</b>	<b>Nozzle Exit (in.)</b>	<b>Mach No.</b>	<b>Stagnation Enthalpy (Btu/lbm)</b>	<b>Pressure Atmosphere</b>	<b>Mass flow (lbm/sec)</b>	<b>Run Time (min)</b>	
High Enthalpy Ablations	H-1	0.75 - 3.0	1.8 - 3.5	600 - 8,500	<120	0.5 - 8	1 - 2	
	H2	5.0 - 42.0	3.4 - 8.3	1,200 - 5,500	<120	2 - 10	3 - 30	
	H3	1.2 - 4.5	1.8 - 3.5	600 - 8,500	<150	3 - 25	1 - 2	
	Tunnel 9	11.3	6.7	900 - 925	52 - 67	18 - 37	3 - 6	
	Tunnel C	25	4, 8	170 - 480	1 - 130	0.6 - 55	Continuous	
<b>Air Breathing Propulsion</b>	<b>Facility</b>	<b>Contoured Nozzle</b>	<b>Test Section Size (in.)</b>	<b>Total Pressure (psia)</b>	<b>Total Temperature (°R)</b>	<b>Pressure Altitude (ft)</b>	<b>Dynamic Pressure (psf)</b>	<b>Usable Run Time (sec)</b>
Supersonic Hypersonic	APTU	Mach 4.3	42 diam	70 - 220	1,825 max	63,700 - 88,400	500 - 1,600	120 - 240
	APTU	Mach 5.2	42 diam	150 - 1,100	2,320 max	54,500 - 96,400	500 - 3,600	90 - 120
		Mach 6.3	42 diam	410 - 1,800	3,233 max	76,000 - 105,000	500 - 2,200	60 - 90
		Mach 7.2	42 diam	960 - 2,800	4,700 max	87,999 - 110,000	500 - 1,450	30 - 60
<b>Space Sensor</b>	<b>Facility</b>	<b>Environment</b>	<b>Image Sources</b>			<b>Background</b>	<b>Run Time</b>	
Sensor Calibration	7V	Sea Level - (15 K, 10 <sup>-7</sup> torr)	2 Independently Moving Precision Blackbody Targets - 800 K Complex Scenes - IR Array, 512 x 512, 45 Hz			15 Kelvin, 10 <sup>-7</sup> torr	Continuous	
3-Color Sensor HWIL	10V	Sea Level - (15 K, 10 <sup>-7</sup> torr)	2 Independently Moving Precision Blackbody Targets - 800 K 2 IR Arrays, 512 x 512, 45 Hz 1 Visible Array, 1,024 x 1,024, 45 Hz			15 Kelvin, 10 <sup>-7</sup> torr	Continuous	
<b>Space Environments</b>	<b>Facility</b>	<b>Test Section Size</b>	<b>Wall Temperature</b>		<b>Pressure Altitude</b>		<b>Run Time</b>	
Electric Propulsion (<50kW)	12V	12 ft diam x 35 ft tall	15 K		10 <sup>-7</sup> torr		Continuous	
Thermal Vacuum	Mark I	42 ft diam x 82 ft tall	77 K		10 <sup>-7</sup> torr		Continuous	
<b>Space Environments</b>	<b>Facility</b>	<b>Environment</b>			<b>Energy</b>	<b>Run Time</b>		
Combined Space	CCOSE	Electrons, Protons, Atomic Oxygen and UV Radiation			Bandwidth	Continuous		
<b>Radiation Environments</b>	<b>Facility</b>	<b>Environment</b>			<b>Energy</b>			
X-Ray Environment	MBS	Cold or Hot X-Ray			MeV			
† Inactive								



# **Appendix 7**

## **AEDC Commanders**

# **AEDC Commanders**



**Maj. Gen. Franklin O. Carroll**  
1950-1952



**Col. Charles K. Moore**  
1952-1953



**Maj. Gen. Sam T. Harris**  
1953-1956



**Maj. Gen. Troup Miller**  
1956-1960



**Brig. Gen. Homer Boushey**  
1960-1961



**Maj. Gen. William L. Rogers**  
1961-1964



**Brig. Gen. Lee V. Gossick**  
1964-1967



**Brig. Gen. Gustav Lundquist**  
1967-1969

**AEDC Commanders**



**Brig. Gen. Jessup D. Lowe**  
1969-1971



**Col. Ward E. Protsman**  
1971-1973



**Col. Webster C. English**  
1973-1975



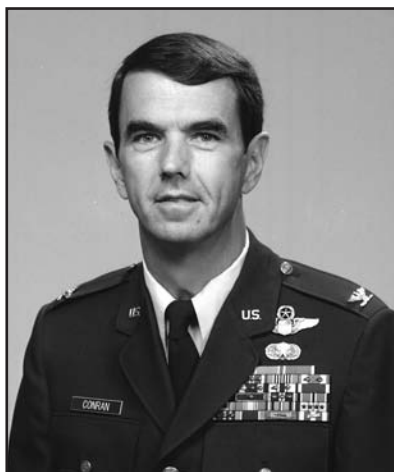
**Col. Oliver H. Tallman**  
1975-1979



**Brig. Gen. Michael H. Alexander**  
1979-1981



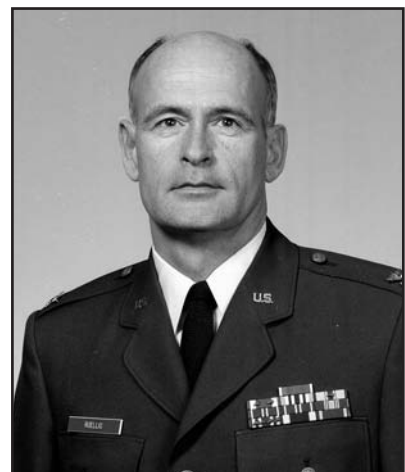
**Brig. Gen. Kenneth R. Johnson**  
1981-1983



**Col. Phillip G. Conran**  
1983-1986



**Col. Stephen P. (Pat) Condon**  
1986-1989

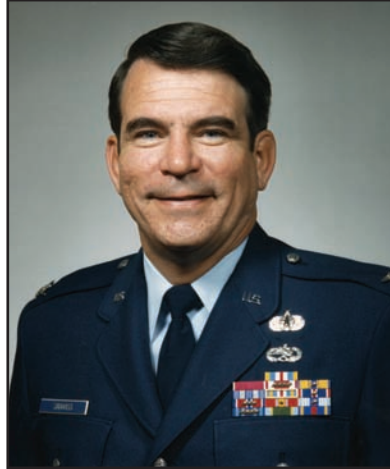


**Col. Richard H. Roellig**  
1989-1991

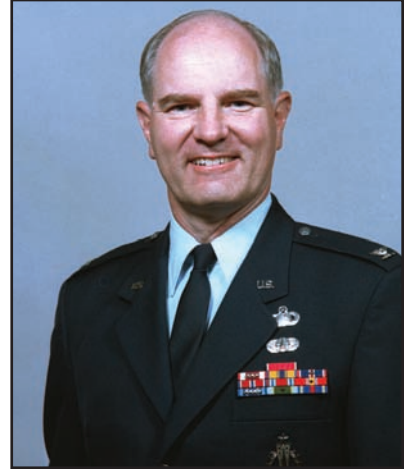
**AEDC Commanders**



**Col. William D. Rutley**  
1991-1993



**Col. Lawrence P. Graviss**  
1993-1995



**Col. Michael P. Wiedemer**  
1995-1997



**Col. Robert W. Chedister**  
1997-1998



**Col. Michael L. Heil**  
1998-2001



**Brig. Gen. David J. Eichorn**  
2001-2004



**Brig. Gen. David L. Stringer**  
2004-2006



**Col. Arthur F. Huber II**  
2006-2009



**Col. Michael T. Panarisi**  
2009-Present





# **Appendix 8 AEDC Fellows**

# AEDC Fellows



*Fellows are listed alphabetically; their selection year is indicated below their photo.*

The AEDC Fellows Program, which was established in 1989, honors individuals who have made substantial and exceptionally distinguished contributions to the nation’s aerospace ground testing capability at AEDC. All military, civilian and operating contractor/subcontractor Team AEDC members, presently or once assigned to AEDC, are eligible. Candidates must have personally made sustained, notable, valuable and significant contributions in aerospace ground testing while at AEDC. Inductees will be honored annually on a date to coincide with the birthday (June 25) of General of the Air Force Henry H. “Hap” Arnold, for whom the award and the installation are named.

The lapel pin is designed to represent the ideals of each of the Fellows; the torch represents a torchbearer who leads the way for others; the flame represents knowledge and enlightenment; and the wings represent flight— aerospace technology.

In 2009, a new category - the AEDC Lifetime Achievement Fellow - was added. This category recognizes individuals who have made significant and exceptionally valuable contributions to AEDC throughout their career.

There have been four honorary AEDC Fellows: General Henry “Hap” Arnold, Gen. Bernard Schriever, Dr. Theodore von Kármán and Dr. Frank Wattendorf.



**Dr. John C. Adams**  
1992



**Richard F. Austin**  
2001



**Dr. William B. Baker**  
2004



**Dr. John Benek**  
2003



**Travis Binion**  
1994



**Temple Bowling**  
Lifetime Achievement -  
2009



**John A. Cable**  
1992



**Dr. James W. Cunningham**  
2006



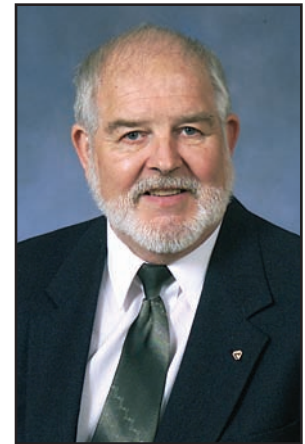
**Dr. Donald Daniel**  
2000



**Dr. John W. Davis**  
1992



**Milton W. Davis, Sr.**  
2006



**Ronald Dawbarn**  
2005



**Robert O. Dietz**  
1989



**Donald R. Eastman**  
1989



**Dr. P. David Elrod**  
2008



**Bernard H. Goethert**  
1989



**Maj. Gen. Lee V. Gossick**  
1991



**Rudy W. Hensel**  
1990



**Dean Herron**  
1997



**Dennis D. Horn**  
1989

**AEDC Fellows**



**Frank M. Jackson**  
2005



**Dr. James Jacocks**  
1996



**Jerry H. Jones**  
2000



**Carl T. Kidd**  
2004



**Dr. William F. Kimzey**  
1991



**Dr. Edward Kraft**  
1994



**Dr. Keith L. Kushman**  
1999



**Dr. Marion L. Laster**  
1991



**T. Frank Langham**  
2007



**Glendon R. Lazalier**  
1995



**Dr. Charles Limbaugh**  
2009



**William (Bill) McDermott**  
2007



**Richard K. Matthews**  
1995



**Paul E. McCarty**  
2007



**Dr. Wheeler K. McGregor**  
1990



**Marvin L. McKee**  
2002



**Dr. James G. Mitchell**  
1989



**Luther Neal, Jr.**  
2001



**Glenn Norfleet**  
2003



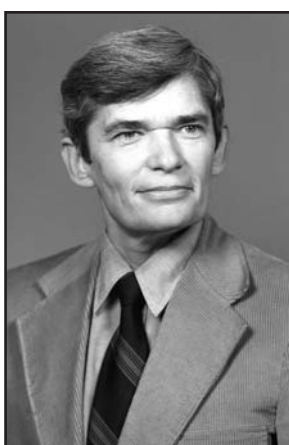
**Dr. Wendell S. Norman**  
2004



**Dr. Samuel R. Pate**  
1991



**David Pickering**  
Lifetime Achievement -  
2009



**Dr. J. Leith Potter**  
1993



**Earl A. Price**  
1999

**AEDC Fellows**



**John Rampy**  
1996



**Dr. Eugene J. Sanders**  
1998



**Frederick L. Shope**  
2006



**Jim Sivells**  
1997



**Forrest B. Smith**  
2000



**Robert E. Smith, Jr.**  
1990



**Dr. Virgil Smith**  
1997



**Wade Stevenson**  
2008



**William T. Strike**  
1995



**W. A. "Al" Turrentine**  
1998



**James C. Uselton**  
2005



**Robert L. P. Voisinet**  
1999



**Donald A. Wagner**  
2005



**Dr. Jack D. Whitfield**  
1989



**Robert M. Williams**  
1993



**Dr. Robert L. Young**  
1994



# **Appendix 8 Contractor Work Force**



# Contractor Work Force

From a presentation by Leif J. Sverdrup, president of ARO, Inc. in 1961, response to budget and bureau from No. 116-6103.

*“The Markham Committee of the Scientific Advisory Board recognized that the normal Air Force and Civil Service regulations, which must cover broad organizations, do not lend themselves, in general, to the flexibility and responsiveness to new circumstances which are required in an R&D organization dealing with rapidly changing products. Regulations which are sound when applied to a stabilized situation may often be totally unsuited to an evolutionary activity. For this reason, suggestions were made that the maximum flexibility should be incorporated in the operating plan for these large facilities. This meant that Air Force regulations, which are applicable to an Air Force base, whether it be in Texas, Spain or Greenland, are not sufficiently adaptable for use where new product development is the goal. Accordingly, the decision was made to place the operation of the facilities in the hands of a private contractor who would be guided by, but not restricted to, the standard Air Force regulations. ARO, then, is an experiment in management and I believe that this experiment may have as great importance to the Air Force R&D program as the actual work of the facilities.*

*“ARO is a wholly owned subsidiary of Sverdrup & Parcel, Inc., the engineering firm responsible for the design of the technical facilities of the center. ARO was formed at the request of the Air Force for the sole purpose of conducting operations at the center for the Air Force. A new organization was required to avoid compromising proprietary information of the contractors whose products would be tested and evaluated.*

*“The first ARO employee was hired in May of 1950.*

*“The mission of ARO is to manage, operate and maintain the facilities of the Arnold Engineering Development Center and to provide personnel, material and services necessary to perform efficiently all operations of the center.*

*“ARO performs those managerial functions necessary to establish the operating plan and to provide the organization to manage, operate, maintain and administer the center facilities and related support services.”*

One distinct feature that sets AEDC apart from other military installations is its contractor work force. At AEDC, contractors make up 90 percent of the work force, performing the bulk of the operations.

A military work force is by design transient. Roughly every two to three years, new personnel transfer in or out, making it difficult to build corporate knowledge.

The original rationale for operating AEDC with private sector personnel included limited availability of qualified technical personnel in the Air Force, either as military or civilians. It also recognized the flexibility afforded by the use of private companies who could hire and terminate employees with much more ease than could the federal government. In addition, a private company has more ability to tailor its pay scales or even individual salaries to market rates, thereby giving them the ability to recruit personnel with special skills who may not be available to the government as federal employees.

The decision to use a for-profit corporation has proved beneficial. Although the original contracts were cost-plus-fixed fee, the contracts over the last 28 years have been cost-plus-award-fee. The award fee feature has enabled the Air Force to use the profit motive to incentivize contractors to continually improve productivity and quality while controlling costs.

In addition, AEDC has seen some benefits from competitive award of the contracts, including more

definitive Air Force control of the operation, more effective cost control and responsiveness of the contractor to Air Force and AEDC customer needs.

As AEDC was being planned and constructed in 1949 and 1950, two separate groups studied the needs of the Air Force for research, development and testing, and the possible methods of operation for AEDC. The Ridenour report titled *R&D in the USAF*, and prepared in 1949, emphasized the need for facilities like those ultimately constructed at AEDC. The report further cited the need to go outside the Air Force for the personnel with the technical expertise needed to operate the facility since the Air Force lacked a sufficient number of military or civilian people with this expertise.

The second report by the Markham Committee titled, ‘Special Committee on AEDC Operation,’ and prepared in 1950, recommended that AEDC be operated by a non-profit corporation. Noting that AEDC facilities would be made available to industry for test, would test items developed for the services and would perform internal research and development (R&D) work, the committee suggested that the non-profit entity should be sponsored by a parent organization which would preferably be a large industrial corporation with a variety of technical interests.

After considering these reports and other information available to him at the time, W. Stuart Symington, then Secretary of the Air Force, decided that the Air Force would

be best served by contracting with a for-profit corporation to operate the facilities, recognizing the value of the profit motive.

The first contract to operate the facilities was awarded in 1950 to Arnold Research Organization (ARO), Inc., a newly formed subsidiary of Sverdrup & Parcel (S&P), the engineering firm that designed the original AEDC facilities. It was important that conflicts of interest be avoided, so contractual language was developed to preclude operation by firms involved in the manufacture of hardware amenable to testing at AEDC. Since S&P was not an aerospace hardware manufacturer, and ARO, Inc., had no business outside AEDC, conflicts of interest were avoided.

ARO, Inc., was awarded a series of contracts on a sole source basis through fiscal year 1977.

However, in 1970 Air Force Assistant Secretary Whitaker published a memorandum directing the Air Force to examine the possibilities of competing several large operating contracts which had been awarded only on a sole source basis for many years.

The AEDC contract was included in that memorandum.

As a result, the fiscal year 1978-1980 contract was the subject of a formal competitive source selection. ARO, Inc., submitted the winning offer.

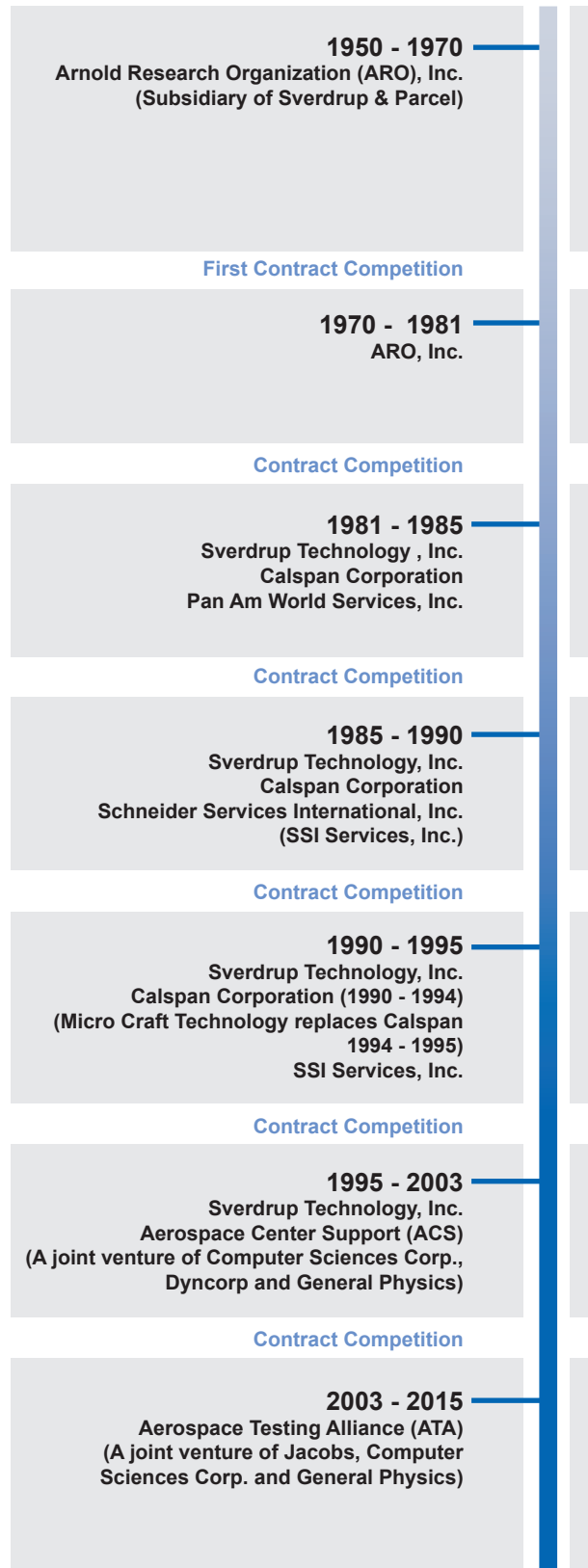
In 1979, AEDC leadership determined that a second source selection for the entire AEDC operation probably would not result in a viable competition. The scope of work was deemed too broad for a single company to compete effectively against a 30-year incumbent, so the Statement of Work was broken into three separate packages.

Effort A covered the propulsion test facilities; Effort B covered the aerodynamic flight test and space simulation facilities; and Effort C represented the mission support functions at the center. The rationale for this split was that there should be several companies in the country who could compete effectively for each narrower portion of the work.

In the source selection for the fiscal year 1981-1985 contracts, Sverdrup Technology, Inc. (formerly ARO, Inc.) won the propulsion test contract, retaining about 25 percent of their former employees. Calspan Corporation, a subsidiary of Arvin Industries, was selected for the flight dynamics work. The winner of the mission support work was Pan Am World Services, Inc., a subsidiary of Pan Am World Airways. The two new firms hired approximately 2,200 of the former ARO, Inc., employees, thereby assuring continued technical expertise in the operation of the center's complex test facilities and support equipment.

In 1985, AEDC conducted a formal source selection for the three efforts in which Pan Am World Services, Inc., was replaced by Schneider Services International (SSI Services, Inc.). Schneider hired about 99 percent of the former Pan Am employees, again retaining the technical expertise needed while bringing in a new management team to stimulate and lead improvements in operating processes

# The Contractors



## AEDC Contractor Work Force

and philosophies. Sverdrup and Calspan were successful in retaining their respective contracts.

In 1990, a competitive source selection resulted in retention of the three incumbent contractors, Sverdrup, Calspan and SSI.

During Calspan's performance of the five-year contract, they formed a joint venture, Micro Craft Technology, with Micro Craft, Inc.

In 1995, a competitive source selection for the fiscal year 1996-2000 contracts was conducted. A follow-on single three-year option was included in the new contracts. These options were exercised in February 2000, extending the performance through fiscal year 2003. ACS, a joint venture of Computer Sciences Corp. (CSC), DynCorp and General Physics, replaced SSI as the support contractor while Sverdrup won the test contract.

ACS and Sverdrup hired approximately 2,850 of the former employees, thereby ensuring continued technical expertise in the operation of the center's complex test facilities and support equipment.

In 2002, the Air Force began a competitive source selection for the Operation, Maintenance, Information Management, and Support of AEDC. The resulting Acquisition strategy resulted in combining the test support

and center Support contracts into a single consolidated contract to maximize innovations and efficiencies; easing of the Organizational Conflict of Interest (COI) clause to increase competition; and proposing a long-term contract (up to 12 years) to foster partnership. The longer term is a combination of options and award terms. This source selection was an agency-level acquisition under the purview of the Air Force Program Executive Office for Combat and Mission Support.

On June 30, 2003, the contract was awarded to Aerospace Testing Alliance (ATA), a joint venture of Jacobs, CSC, and General Physics.

ATA hired approximately 2,200 of the former employees, again ensuring the continued technical expertise needed to operate of the center's complex test facilities and support equipment. The first one-year option under this contract was exercised in August 2004; contract options have been exercised yearly since 2004.

AEDC has been Air Force-managed and contractor operated for almost 60 years. The rationale originally used in selecting this mode of operation was valid at the time, and even though many things have changed since 1950, the rationale remains so today.

## AEDC Total Work Force 1950-2008

