CHAPTER THREE

AERONAUTICS AND SPACE RESEARCH AND TECHNOLOGY

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Introduction

The federal government's involvement with aeronautics preceded NASA's establishment by many years. In 1915, Congress mandated that the National Advisory Committee for Aeronautics (NACA) "supervise and direct the scientific study of the problems of flight, with a view to their practical solution." In the National Aeronautics and Space Act of 1958 that established NASA, Congress stated that NASA would be involved in "aeronautical and space activities" using "aeronautical and space vehicles." The law defined aeronautical and space activities as:

(a) research into, and the solution of, problems of flight within and outside the Earth's atmosphere; (b) the development, construction, testing, and operation for research purposes of aeronautical and space vehicles; (c) the operation of a space transportation system including the Space Shuttle, upper stages, space platforms, and related equipment; and (d) such other activities as may be required for the exploration of space.[1]

It also defined aeronautical and space vehicles as "aircraft, missiles, satellites, and other space vehicles, manned and unmanned, together with related equipment, devices, components, and parts."[2] It can safely be said that NASA Office of Aeronautics and Space Technology (OAST) activities have covered all these areas.

OAST's aeronautics research and technology program from 1979 to 1988 was derived from several technological disciplines and spanned the flight spectrum from hovering to hypersonic aircraft. OAST provided technology results well in advance of specific applications needs and conducted long-term independent research without

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[1] "Aeronautics: The NASA Perspective," NASA Fact Sheet, February 10, 1981.

[2] U.S. Congress, *NASA Aeronautics and Space Act of 1958 (as Amended),* sec. 103 (Washington, DC: U.S. Government Printing Office, 1958).

the payoff of known immediate mission applications. The disciplinary research applied to all classes of vehicles and related to capabilities that were yet undefined. In addition, OAST's technology research enhanced the capabilities of specific classes of vehicles, such as subsonic transport, rotorcraft, high-performance military aircraft, and supersonic and hypersonic vehicles.

Space research and technology took both a disciplinary approach and a vehicle-specific approach. Disciplines represented in the program included propulsion, space energy, aerothermodynamics, materials and structures, controls and guidance, automation and robotics, space human factors, computer science, sensors, data and communications systems, and spaceflight systems. The space research and technology program developed and improved technologies and components for the Space Shuttle and for the future Space Station and also participated in missions and experiments launched from and conducted on the Shuttle.

OAST's fundamental involvement with other agencies and with industry differed from other NASA organizations. In the area of general aviation, OAST worked with the Federal Aviation Administration (FAA), the Department of Transportation, and aircraft manufacturers to improve aircraft and aviation safety and to lessen any harmful impact of flight on the environment. In the area of high-performance aircraft, OAST research supported the needs of the military, and NASA continually participated in joint projects with the Department of Defense (DOD) and sometimes shared the financial costs of these projects.

OAST's activities have benefited the U.S. economy. Congress regularly, in its deliberations on NASA's budget, noted that aeronautics was one area in which the United States had a positive balance of trade and also contributed to creating a large number of jobs. Congress generally deemed NASA's aeronautics deserving of steady support. For instance, in the Conference Report that accompanied the FY 1982 budget authorization, the committee expressed its concern

> *with a recent trend toward lower levels of Federal support for aeronautical research and technology development. NASA's research and technology for decades has been the wellspring for U.S. aviation development from which the nation's military, commercial, and general aviation leadership has evolved. This has meant millions of jobs for Americans with a wide range of trade and professional skills in every region of the country. It has meant billions in favorable balance of trade over the years. . . . It has meant billions of dollars returned to the Federal treasury in tax revenues.*[3]

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[3] "Authorizing Appropriations to the National Aeronautics and Space Administration," Conference Report, November 21, 1982, *Chronological History FY 1982 Budget Submission,* prepared by the NASA Comptroller, Budget Operations Division, p. 51.

This recognition of the benefits of NASA's aeronautics activities helped OAST secure a reasonably steady level of funding.

From 1979 to 1988, three policy statements issued by the Executive Office of the President's Office of Science and Technology Policy (OSTP) helped define OAST's focus. The first policy statement resulted from a 1982 multi-agency review of national aeronautical research and technology policy. The group, chaired by Victor Reis, assistant director of OSTP, addressed two questions:

1. Was aeronautics a mature technology, and was continued investment justified by potential benefits?
2. What were the proper government roles in aeronautical research and technology, and did the present institutional framework satisfy these roles or should it be changed?

The group stated that the aerospace industry "has evolved into a major U.S. enterprise that provided about 1.2 million jobs in the United States in 1981." It concluded that "the present institutional framework allowed implementation of the U.S. government role in developing aeronautical research and technology." It recommended that the government meet the following national aeronautics goals:

Aeronautics

1. Maintain a superior military aeronautical capability
2. Provide for the safe and efficient use of the national airspace system, vehicles operated within the system, and facilities required for those operations
3. Maintain an environment in which civil aviation services and manufacturing can flourish
4. Ensure that the U.S. aeronautical industry has access to and is able to compete fairly in domestic and international markets consistent with U.S. export policy

Aeronautical Research and Technology

1. Ensure the timely provision of a proven technology base to support future development of superior U.S. aircraft
2. Ensure the timely provision of a proven technology base for a safe, efficient, and environmentally compatible air transportation system[4]

OSTP, chaired by G.A. Keyworth II, science advisor to the President, issued the second policy statement in March 1985. It spelled out specific

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[4] "Aeronautical Research and Technology Policy," Vol. I: Summary Report, Executive Office of the President, Office of Science and Technology Policy, November 1982, pp. 14, 21–23.

goals in subsonics, supersonics, and transatmospherics. These goals were the basis for NASA's future aeronautics program planning.[5]

The subsonic goal aimed to provide technology for an entirely new generation of fuel-efficient, affordable U.S. aircraft operating in a modernized national airspace system. The supersonic goal focused on developing "pacing technologies" for sustained supersonic cruise capability for efficient long-distance flight. The transatmospheric goal encompassed the pursuit of research toward a capability for extremely fast passenger transportation between points on Earth, as well as for a vehicle that could provide routine cruise and maneuvers into and out of the atmosphere with takeoffs and landings from conventional runways.

The third policy statement, issued in February 1987, stated that although the United States had made progress in reaching the 1985 goals, "greater achievement" was necessary. The committee, chaired by the science advisor to the President, William R. Graham, presented an eight-point action plan to achieve the national goals and "remain a viable competitor in the world aviation marketplace."[6] The action plan summary was as follows:

1. Increase innovative industry research and development efforts given the certainty of intensifying global competition and the importance of new technology for U.S. competitiveness
2. Aggressively pursue the National Aerospace Plane program, assuring maturation of critical technologies leading to an experimental airplane
3. Develop a fundamental technology, design, and business foundation for a long-range supersonic transport in preparation for a potential U.S. industry initiative
4. Expand domestic research and development collaboration by creating an environment that reflects the new era of global competition
5. Encourage government aeronautical research in long-term emerging technology areas that provide high payoffs
6. Strengthen American universities for basic research and science education through enhanced government and aerospace industry support and cooperation
7. Improve the development and integration of advanced design, processing, and computer-integrated manufacturing technologies to transform emerging research and development results into affordable U.S. products

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[5] "National Aeronautical R&D Goals: Technology for America's Future," Executive Office of the President, Office of Science and Technology Policy, March 1985.

[6] "National Aeronautical R&D Goals: Agenda for Achievement," Executive Office of the President, Office of Science and Technology Policy, February 1987.

8. Enhance the safety and capacity of the National Airspace System through advanced automation and electronics technology and new vehicle concepts, including vertical and short takeoff and landing aircraft

The Last Decade Reviewed (1969–1978)

From 1969 to 1978, NASA carried out aeronautics and space research and technology activities in two organizations: the Office of Advanced Research and Technology (OART) until 1972 and OAST beginning in 1972. The goals were to build a research and technology base, conduct systems and design studies, and carry out systems and experimental programs. Work included the broad categories of air transportation system improvement, spacecraft subsystem improvement, support to the military, and the application of technology to nonaerospace systems.

Research

Until 1970, NASA included basic research as one of its major divisions. The results of basic research added to the pool of knowledge and did not apply to any ongoing project. This program was divided into four sections: fluid dynamics, electrophysics, materials, and applied mathematics.

Space Vehicle Systems

This division dealt with problems vehicles might encounter during launch, ascent through the atmosphere, spaceflight, and atmospheric entry. NASA conducted research in the areas of lifting-body research and planetary entry research.

Guidance, Control, and Information Technology

From 1969 to 1978, NASA worked at improving the operational electronics systems, while reducing their size, weight, cost, and power requirements. Several NASA centers directed a variety of projects with this goal in mind.

Human Factor Systems

This directorate was responsible for the human factors systems program, which held that humans were a critical component of the spacecraft system or part of a human-machine system. Investigators were concerned with the interaction between the pilot/astronaut and the vehicle that affected health, comfort, survival, and decision-making skills. NASA conducted research into the various systems that were found on aircraft and that would be found on the Space Shuttle. Researchers also investigated long-term exposure to the space environment.

Space Power and Propulsion Systems

Researchers during the 1970s investigated lighter, more efficient propulsion systems than the chemical propulsion systems of the 1960s. Both electric and nuclear propulsion received much attention. Efforts in chemical propulsion were devoted to solving the Shuttle's main engine design problems. NASA also carried out joint research into nuclear propulsion with the Atomic Energy Commission. In addition, NASA tested various methods of generating power using chemical, electric, and nuclear sources.

Aeronautics

NASA reorganized OART in 1970 to emphasize improving aeronautical research, which NASA had been accused of neglecting. Both staff and budget levels were increased to provide additional resources. NASA abolished basic research divisions and carried out aeronautics activities in three offices—aeronautical operating systems, aeronautical research, and aeronautical propulsion—and had special offices devoted to short takeoff and landing (STOL) aircraft and experimental transport aircraft. It also added an office for the Military Aircraft Support Program. The Aeronautics Division conducted projects in the areas of general aviation, environmental factors, vertical/STOL aircraft, supersonic/hypersonic aircraft, and military support.

Aeronautical and Space Research and Technology (1979–1988)

OAST focused on aeronautical research and technology and on space research and technology. Within these two major areas, work took place in two prime fields: research and systems. Research was generally disciplinary in nature and focused on aerodynamics, materials and structures, propulsion, aerothermodynamics, energy conversion, controls and human factors, computer science, and information sciences. Systems-focused work was often multidisciplinary and had more immediate application. NASA's systems activities supported existing NASA projects such as the Space Shuttle, developed enabling technology for future projects such as the Space Station, and provided support to the military.

In addition, in the early part of the 1980s, OAST supported national energy needs through its Energy Technology Program. The Department of Energy and other federal agencies sponsored NASA's work in this area, which encompassed a variety of projects. These included solar cell power systems, automotive power systems, industrial gas turbine development, solar heating and cooling, wind turbine generators, solar thermal electric conversion, energy storage, and advanced coal extraction and processing.

Aeronautics

Many OAST efforts focused on improving flight efficiency. Beginning in the 1970s and continuing into the 1980s, the Aircraft Energy Efficiency program spanned several disciplines and focused on developing solutions that could be applied to existing vehicles, to their spinoffs expected within a few years, and to new classes of aircraft designed specifically to be fuel efficient. New advances in turboprop research promised considerable fuel savings while maintaining the performance and cabin environment of modern turbofan aircraft. New composite materials were also being developed that would result in reduced cost and weight. In addition, OAST analyzed ways to increase lift and reduce drag in wings, shaping them to meet the needs of the new generation of aircraft. Aircraft drag reduction research emphasized techniques for maintaining laminar boundary-layer airflow over larger segments of aircraft wings and other surfaces. In addition, the oblique wing was extended to the requirements of supersonic flight and showed increased fuel economy. Other wing configurations also added to flight efficiency.

Another research target was the large-capacity STOL aircraft. STOL and vertical takeoff and landing (VTOL) aircraft were planned for use at airports located close to populated areas. These locations demanded aircraft with a low noise level. NASA, along with industry, developed an experimental engine that produced a significant reduction in generated noise. The quiet, clean, short-haul experimental engine had a goal of providing power for a four-engine, 150-passenger STOL transport that generated relatively low noise. This engine began test runs at Lewis Research Center in the late 1970s.The Quiet Short-haul Research Aircraft (QSRA), evaluated by Ames Research Center, was another “quiet” aircraft that incorporated the propulsive lift system.

Related developments in propulsion system thrust-to-weight ratios, propulsive lift control, and understanding low-speed aerodynamics provided advances in vertical and short takeoff and landing (V/STOL) and short takeoff and vertical landing (STOVL) technology. In 1986, the United States and the United Kingdom signed a joint research agreement to develop advanced STOVL (ASTOVL) technologies and to reduce the risks associated with developing this type of aircraft. Also, NASA and Canada agreed to test a full-scale STOVL model designated as the E-7.

Rotary wing aircraft was another primary focus of NASA’s aeronautics activities during this decade. Capable of STOL and VTOL performance, rotorcraft had both civilian and military applications. Two flight vehicles formed the cornerstones of NASA’s rotorcraft research. The Tilt-Rotor Research Aircraft had twin rotors and power plants mounted at the ends of a high wing. The rotors could be tilted from horizontal, permitting vertical flight, to vertical, permitting horizontal flight. The Sikorsky Rotor Systems Research Aircraft (RSRA) used helicopter rotor heads as the basic lifting system but were designed to be able to test a wide variety of rotor systems. The RSRA could be flown as a conventional helicopter, or as a compound helicopter, with fixed wings installed to "unload" the rotor by assuming some of the lift. Both aircraft flew out of Ames Research Center and at other locations.

Aviation safety has traditionally been a focus of NASA aeronautical research. During this decade, NASA carried out research on wind shear, icing, heavy rain, lightning, and combustible materials on aircraft. NASA conducted many of these activities cooperatively with the FAA.

One of NASA's aeronautics missions was to provide support to the military. The Highly Maneuverable Aircraft Technology (HiMAT) program worked with the military to resolve the problems associated with combining high maneuverability, high speed, and a human pilot. The project had two basic tasks: to study the interrelated problems of all aspects of the flight of a typical advanced fighter configuration and to contribute to the design of future fighter types by furnishing fundamental aerodynamic and structural loads data to assist designers. The HiMAT remotely piloted research vehicle made its first flight on July 27, 1979, from Dryden Flight Research Center.

In 1985, the X-29A flight research program began. The unique forward-swept wing of the aircraft was made of composite materials that reduced the wing's weight up to 20 percent, compared to the weight of conventional aft-swept wings. The forward-mounted "canards" were computer-adjusted forty times a second to improve flight efficiency and aircraft agility. [7]

A new convertible gas turbine engine and other propulsion systems were developed and demonstrated at Lewis Research Center. The gas turbine engine allowed the engine's output to take the form of either shaft power or fan power. This type of propulsion system was required for advanced high-speed rotorcraft concepts such as the X-wing, in which rotor blades operating in a spinning mode for takeoff and landing were stopped and locked in place as an X-shaped fixed wing for high-speed flight. A propfan propulsion system, also developed and tested at Lewis, received the 1987 Robert J. Collier Trophy for developing the technology for and testing of advanced fuel-efficient subsonic aircraft propulsion systems.

In his 1986 State of the Union address, President Ronald Reagan announced the initiation of the joint NASA-DOD National Aerospace Plane research program that was planned to lead to an entirely new family of aerospace vehicles. Reagan stated that "we are going forward with research on a new Orient Express that could, by the end of the next decade, take off from Dulles Airport [located near Washington, D.C.], accelerate up to 25 times the speed of sound, attaining low Earth orbit or flying to Tokyo within two hours."[8] The goal of the program was to develop hypersonic and transatmospheric technologies for a new class of aero-

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[7] Canards are horizontal stabilizers used to control pitch.

[8] "State of the Union Address," in *Presidential Papers of Ronald Reagan* (Washington, DC: U.S. Government Printing Office, February 1986).

space vehicles characterized by horizontal takeoff and landing, single-stage operation to orbital speeds, and sustained hypersonic cruise within the atmosphere using airbreathing rather than rocket propulsion. These technologies, it was hoped, would lead to a new flight research vehicle (the X-30). Between 1986 and 1989, the main goal of the technology development phase was to develop and test an integrated airframe/propulsion system that could operate efficiently from takeoff to orbit. A series of developmental contracts awarded during 1986 and 1987 focused on propulsion systems and certain aircraft components.

Several new NASA facilities supported OAST's research programs. In 1985, a new National Transonic Facility opened at Langley Research Center that permitted engineers to test models in a pressurized tunnel in which air was replaced by the flow of supercooled nitrogen. As the nitrogen vaporized into gas in the tunnel, it provided a medium more dense and viscous than air, offsetting scaling inaccuracies of smaller models tested in the tunnel. In 1987, the Numerical Aerodynamic Simulation Facility, located at Ames, became operational. It could make 1 billion calculations per second. For the first time, aircraft designers could routinely simulate the three-dimensional airflow patterns around an aircraft and its propulsion system. Also at Ames, a complement to the existing 12.2-meter by 24.4-meter closed-circuit tunnel became operational at the end of 1987. It had a test section 24.4 meters high and 36.6 meters wide, three times as large in cross-section as the parent tunnel. The original tunnel's fans were also replaced, raising its speed from 370 to 555 kilometers per hour.

Space

NASA's space research and technology program provided advanced technology to ensure continued U.S. leadership in civil space programs. The program focused on technology to develop more capable and less costly space transportation systems, large space systems with growth potential such as the Space Station, geosynchronous communications platforms, lunar bases, crewed planetary missions, and advanced scientific, Earth observation, and planetary exploration spacecraft. All NASA centers were involved, along with significant industry and university participation.

Many of NASA's space technology programs from 1979 to 1988 were concerned with the problems of providing power, controls and structures, and assembly of large space structures. Other research areas included spacesuit studies, research for more efficient reentry from space, advanced power systems for future lunar and Mars bases, and lighter weight tanks for cryogenic fuels. Still other investigations concentrated on control systems for future large lightweight spacecraft and the assembly of large space structures with teleoperated manipulators, as well as a program to allow free-flying telerobots to grapple and dock with gyrating satellites to stabilize and repair the spacecraft.

OAST and the NASA centers were heavily involved with the Space Shuttle. They developed and demonstrated the Shuttle's thermal protection system and continued to improve the composition and durability of the materials. They developed the experiments for the Orbiter Experiments Program, which flew on the first Space Shuttle mission. This program evaluated the aerodynamic, aerothermodynamic, acoustic, and other stress phenomena involved in spaceflight, particularly during the orbiter's return to the atmosphere at hypersonic velocity. OAST participated in Shuttle payloads, developing the Long Duration Exposure Facility and many of its experiments that flew on STS 41-C in 1984, as well as the OAST-1 mission, which flew on STS 41-D, also in 1984.

Many of OAST's technology activities were applicable to Space Station development. Researchers at Langley Research Center and Marshall Space Flight Center developed a mobile work station concept from which astronauts in spacesuits could assemble large structures in space. Methods were developed for the "toolless" assembly of large structures in the weightless environment of space using lightweight composite columns and unique specialized joints. Automation and robotics were important OAST discipline areas. The ACCESS and EASE experiments on STS 61-B tested assembling erectable structures in space.

A major effort went into improving the batteries, solar cells, and solar arrays used on spacecraft. Solar cell and solar array technology improved conversion efficiency, reduced mass and cost, and increased the operating life of these essential components.

The space research and technology program also provided development support for the planetary program and the Earth-orbiting spacecraft programs. OAST developed a computer program that used artificial intelligence techniques to perform automatic spacecraft operations for use on the Voyager project during the Uranus encounter in 1986. In a different area, one of the barriers to planetary return missions was the cost and complexity of return propulsion. Planetary return missions would be less costly if propellant could be produced at or on the planet. OAST researchers successfully demonstrated methods for producing liquid oxygen from a simulated Martian atmosphere by using electrolytic techniques.

In 1987, NASA's Civilian Space Technology Initiative began. Its objective was to advance the state of technology in key areas in which capabilities had eroded and stagnated over the previous decade. This program had a short-term perspective—it was designed to address high-priority national and agency needs of the 1990s.[9] The program included research in technologies to enable efficient, reliable access to and operations in Earth orbit and to support science missions. The program had three technology thrusts: space transportation, space science, and space operations. NASA also encouraged academic sector participation through programs such as the University Space Design program and the University Space Engineering Research program.

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[9] *Aeronautics and Space Report of the President, 1988 Activities* (Washington, DC: U.S. Government Printing Office, 1990), p. 59.

Management of NASA's Aeronautics and Space Technology Program

As mentioned in the previous section, OAST had two primary focuses: aeronautics research and technology and space research and technology. In addition, for a period of time, the office also managed a program for energy technology. Until its August 1984 reorganization, OAST had a division devoted to aerospace research that managed the various discipline areas, an aeronautical systems division, and a space systems division (Figure 3–1). The research division was called the Research and Technology Division until mid-1982 and then the Aerospace Research Division until August 1984.The Aeronautical Systems and Space Systems Divisions managed vehicle-specific and system-specific activities. The disciplinary areas changed slightly between 1979 and 1984. Under the Research and Technology Division were offices for Electronics and Human Factors, Aerodynamics, Materials and Structures, Propulsion, and Space Power and Propulsion. Under the Aerospace Research Division were offices for Controls and Human Factors, Computer Science and Electronics, Fluid and Thermal Physics, Materials and Structures, and Space Energy Conversion.

After the August 1984 reorganization, OAST had two divisions that managed system-related and vehicle-specific work, the Aeronautics Division and the Space Division, as well as a number of disciplinary divisions. The disciplinary divisions interacted with both the Aeronautics and Space Divisions. When the National Aerospace Plane program was established, it became a separate program office (Figure 3–2).

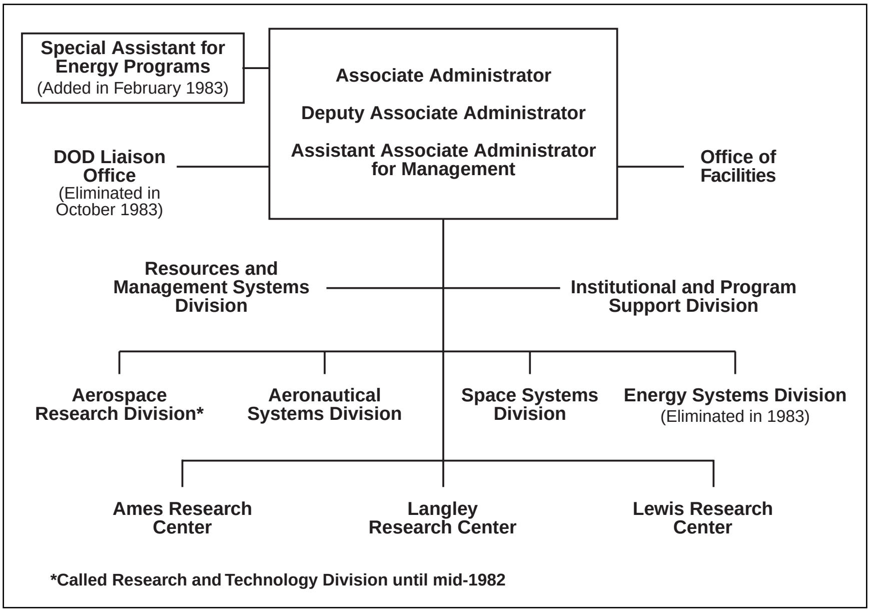

Figure 3–1. Office of Aeronautics and Space Technology (as of October 5, 1983)

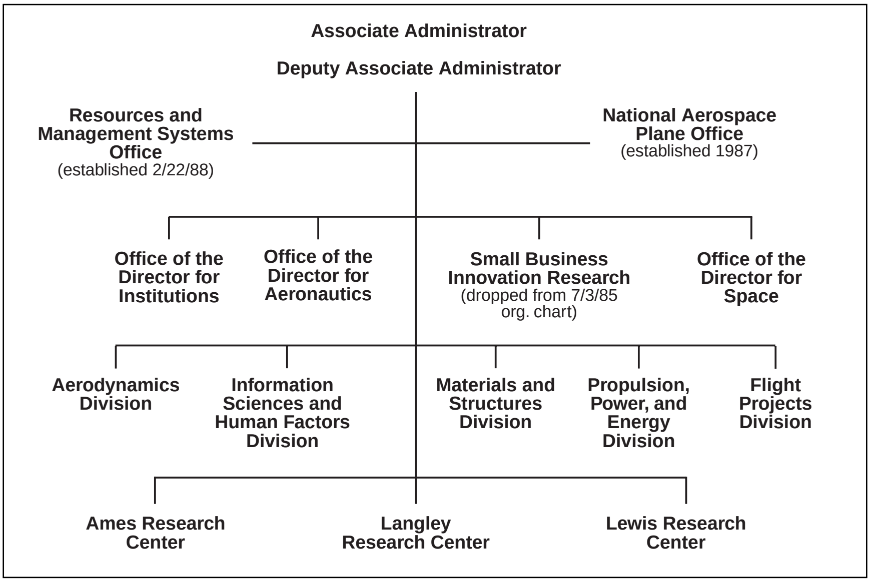

Figure 3–2. Office of Aeronautics and Space Technology (as of August 14, 1984)

OAST also had management responsibility for Ames Research Center at Moffett Field, California, Langley Research Center in Hampton, Virginia, and Lewis Research Center in Cleveland, Ohio. These centers conducted almost all of NASA's aeronautics technology research as well as a considerable amount of space technology research. Dryden Flight Research Facility in Edwards, California, which had been an independent NASA center, became a directorate of Ames Research Center on October 1, 1981. Aeronautical and research activities at the two locations were integrated and staff functions combined. This arrangement continued until 1994, when Dryden again became an autonomous NASA center.

Phase I (Pre-1984 Reorganization)

James Kramer served as associate administrator from October 23, 1977, until his retirement on September 30, 1979. He was replaced by Walter B. Olstad, who served as acting associate administrator until Dr. Jack Kerrebrock became the next associate administrator in June 1981. Kerrebrock remained at that post until July 1983. Dr. Raymond S. Colladay followed and served briefly as acting associate administrator until John J. Martin took the reins at the start of 1984. He remained in place through the 1984 reorganization until April 1985.

Division directors in place at the beginning of 1979 were:

- Donald A. Beattie, director of the Energy Systems Division
- William S. Aiken, Jr., acting director of the Aeronautical Systems Division

- Dell P. Williams, III, acting director of the Space Systems Division
- George C. Deutsch, director of the Research and Technology Division

Beattie remained in place until the Energy Systems Division was disestablished at the end of 1982. Aiken moved from acting division director to division director of the Aeronautical Systems Division in 1981 and remained at that post through the 1984 reorganization. Williams remained with the Space Systems Division until 1983, when Henry O. Slone became acting director, followed by Dr. Leonard A. Harris, who was acting director until he was appointed division director in 1984. Deutsch led the Research and Technology Division until 1981, when Frederick Povinelli succeeded him as acting director. Raymond Colladay became director in July 1981 and remained until the formation of the Aerospace Research Division in 1982. Dr. Leonard A. Harris led the Aerospace Research Division until he was replaced by Cecil C. Rosen III, who served as acting director until the 1984 reorganization.

Phase II (Post-1984 Reorganization)

John Martin remained as associate administrator until April 1985 when Raymond Colladay became acting associate administrator. Colladay was appointed associate administrator effective June 14, 1985. He remained at that post until February 1988, when Dr. William F. Ballhaus, Jr., became acting associate administrator, followed by Dr. Robert Rosen as acting associate administrator later in 1988.

The Aeronautical Systems Division became the Aeronautics Division with the 1984 reorganization. William Aiken, Jr., served as director for Aeronautics until Cecil Rosen III became acting director in mid-1985. He was appointed as division director later that year.

The Space Systems Division was renamed the Space Division, with Leonard Harris serving as director. He remained at that post until mid-1987, when James T. Rose briefly took the position. Frederick Povinelli later became director in October 1987.

Individual disciplinary divisions replaced the Aerospace Research Division in the August 1984 reorganization. Division directors at the time of the reorganization were:

- Information Sciences and Human Factors—Lee B. Holcomb
- Aerodynamics—Gerald G. Kayten
- Materials and Structures—Samuel L. Venneri
- Propulsion, Power, and Energy—Linwood C. Wright (acting)
- Flight Projects—Jack Levine

Kayten remained as Aerodynamics Division director until Dr. Randolph A. Graves assumed the post first as acting director in late 1986 and then as division director in 1987. He left in 1988, and Paul Kutler became acting division director for a brief period.

Wright remained as acting director of the Propulsion, Power, and Energy Division until Robert Rosen became division director in mid-1985. Rosen was followed by Edward A. Gabris in 1986. He remained until Gregory Reck assumed the post as acting director in late 1987 and then as director early in 1988.

Duncan E. McIver was the first director of the National Aerospace Plane Office, which was formed in 1987.

Money for Aeronautics and Space Research and Technology

NASA's funding for aeronautics and space research and technology activities grew in real dollars during the decade but decreased as a percentage of NASA's total budget. Taking into account the rate of inflation during the 1980s, the buying power of the additional dollars may have been negligible. Tables 3–1 through 3–61 show the funding for these activities.

Aeronautics and Space Research and Technology Programs

In FY 1987, total programmed funding jumped more than $13.6 million as the new Civil Space Technology Initiative became part of the budget. This program included focused systems technology programs supporting transportation, operations, and science consistent with the goals of the U.S. space program. In all, from 1979 to 1988, the OAST budget comprised between 6.8 and 10.8 percent of the total NASA Research and Development (R&D) budget (including Space Flight Control and Data Communications, or SFC&DC) (Figure 3–3).

Programmed funding for aeronautics and space research programs often differed from the amounts that Congress authorized or appropriated, even when Congress specified funding for a particular activity. NASA's aeronautics and space research activities were more intertwined with both military priorities and the activities of industry than the agency's programs in other areas. Thus, whether one of NASA's programs continued or was cancelled depended somewhat on whether

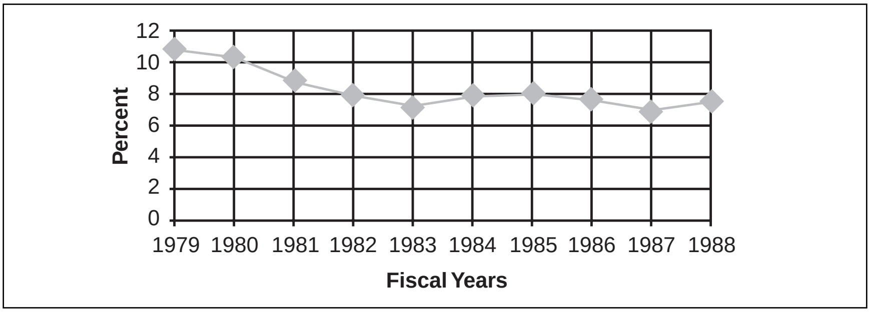

Figure 3–3. Percentage of R&D and SFC&DC Budget Allocated for Office of Aeronautics and Space Technology Activities

the military or industry shared some of the funding burden. The reduction or elimination of funding from non-NASA sources part way through a program could have forced temporary or permanent cessation of the activity.

Budget data in this section (request or submission, authorization, and appropriation) for the major budget categories come from the annual Budget Chronological Histories. Request or submission data for the more detailed budget items comes from the annual budget estimates produced by NASA's Budget Office. No corresponding authorization or appropriations data for these activities were available. All programmed (actual) figures come from NASA's Budget Office budget estimates. (Note that these "budget estimate" volumes contain estimates for a future period as well as actual amounts for a period that has ended.)

During FY 1979, a significant reordering of budget categories took place. Thus, the budget categories that were used for the budget requests often no longer existed by the time the programmed or actual budget was known. This was especially true in the Spacecraft Research and Technology area. Sometimes it is obvious from the item description that only a name change took place or two categories merged into one. These are noted. However, in other cases, no obviously equivalent budget category was substituted. These are also noted.

Aircraft Energy Efficiency Program

The Aircraft Energy Efficiency Program was a joint effort funded by NASA and industry. It included activities that fell in the Transport Aircraft Systems Technology and the Advanced Propulsion Systems areas of the Systems Technology Program. The budget categories listed in Table 3–21 were funded prior to FY 1979. Engine Component Improvement terminated in FY 1981, Advanced Turboprops received funding through FY 1985, and Composite Primary Aircraft Structures received funding through FY 1983. The other budget categories received funding through FY 1982.

Aeronautics Research and Technology Programs

NASA's aeronautics programs have been noteworthy in the extent that they have been cooperative efforts with other government agencies—particularly DOD through its Defense Advanced Research Projects Agency (DARPA) and the FAA—and with industry. Many NASA aeronautics research efforts began at the suggestion of industry or other agencies or because industry or the military identified a need and a large proportion of NASA-developed technologies saw their practical demonstration in the commercial or military sector. The following sections address aeronautics programs in the areas of flight efficiency, high-performance aircraft, and aircraft safety and operations.

Flight Efficiency

Aircraft Energy Efficiency Program

The oil crisis of the 1970s focused attention on the cost and efficient use of fuel and led Congress to push NASA to develop ways to increase fuel efficiency. NASA's Aircraft Energy Efficiency (ACEE) program, a NASA-industry effort, examined the problem of fuel efficiency and worked to develop solutions that could be applied to existing transports, to derivative vehicles expected within the next few years, and to new classes of aircraft designed specifically to be fuel efficient.

The basic goal of the ACEE program was to learn how to use fuel energy more efficiently for propulsion and lift. The program worked on improving aircraft engines, reducing drag of aircraft as they traveled through the atmosphere, decreasing the weight of the materials that comprised airframes, and finding more efficient ways of propelling aircraft through the atmosphere. Researchers believed that reductions in drag, as well as other improvements in the ratio of lift to drag, would improve the range capabilities of aircraft and reduce the operating cost of aircraft. In addition, new materials and structural concepts, combined with the use of active controls, could produce lighter and smaller airframes.

NASA initiated the program in FY 1976 following the oil embargo of the Organization of the Petroleum Exporting Countries (OPEC). Although the program was originally motivated by fuel conservation concerns, it was soon apparent that in addition to fuel savings, improving technology for aircraft and engine efficiency could also improve the competitive position of the United States in the worldwide multibillion dollar air transport marketplace. Industry shared the ACEE costs with NASA.

The cross-disciplinary program included six subsonic technologies or programs: Engine Component Improvement, Energy Efficiency Engine, Advanced Turboprop Program, Energy Efficient Transport, Composite Primary Aircraft Structures, and Laminar Flow Control. Several NASA centers participated in the program. Langley Research Center was responsible for technology programs in aerodynamics and in materials and structures. Langley and Ames Research Center shared wind tunnel testing. Dryden Flight Research Center conducted flight research. Lewis Research Center carried out propulsion research.[10]

The program demonstrated the benefits of NASA-industry cooperation in developing and validating advanced technology for use in civil applications. In addition, many of the concepts had future applications for both civil and military transport.

Engine Component Improvement. This project involved improving existing engine components by using improved aerodynamics and mate-

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[10] "Propulsion/ACEE," *NASA Facts,* NF-93/8-81 (Washington, DC: U.S. Government Printing Office, 1981), pp. 1–2.

rials, applying clearance control techniques, and increasing the bypass ratio. It produced engine component technology for significantly better performance and performance retention in engine retrofits and new projects. Elements included fan blade improvements, turbine aerodynamics, blade cooling seals, and active clearance control. It projected a fuel saving of 5 percent. Applications appeared as early as 1978 and were applied to all modern transport engines. General Electric and Pratt & Whitney took part in this project.

Energy Efficient Engine. This program, completed in 1983, made possible a much greater reduction in cruise fuel consumption and accelerated technology readiness for incorporation into a new generation of fuel-efficient engines than was possible with earlier engines. The program's technologies included compressor, fan, and turbine-gas-path improvements; improved blading and clearance control; and structural advances. The program demonstrated or identified design and technology advances that could reduce turbofan engine fuel consumption by an estimated 15 to 20 percent. Technology derived from the program was applied to the CF6-80C, PW2037, and PW4000 engines. General Electric and Pratt & Whitney also participated in this program.

Energy Efficient Transport. This project focused on aerodynamic and control concepts, such as high-aspect-ratio, low-sweep supercritical wing technology, new high-lift devices; propulsion-airframe integration, digital avionics, and active controls. It led to the application of winglets and the wing load alleviation system.

Composite Primary Aircraft Structures. This project was built on previous NASA composite research and cooperative efforts with industry in the development and flight service validation of secondary structural components. Researchers fabricated and successfully flight-tested primary composite empennage structures, but efforts did not progress as planned to the validation of large wing and fuselage structures, nor did the project resolve manufacturing technology or cost problems.

Laminar Flow Control. This research was also part of the ACEE program. It is addressed elsewhere in this chapter.

Advanced Turboprop Project. This project was directed at greater efficiency for future turboprop-powered aircraft cruising at or near jet transport speed (Mach 0.65 to 0.85). The advanced turboprop, or unducted fan, technology was an important option for medium-range transports with fuel savings of 25 percent or more, as compared to equally advanced turbofan engines. The project successfully tested thin, swept-tip, multi-bladed, high-speed single-rotation, as well as dual-rotation, geared and ungeared versions of turboprop propulsion systems.

This project was the most successful of the ACEE efforts. Lewis Research Center and its industry team received the 1987 Robert J. Collier Trophy for their accomplishments in this area. They were recognized for developing the technology and testing advanced turboprop propulsion systems that provided dramatic reductions in fuel usage and operating costs for subsonic transport aircraft.

Although the rewards were the greatest of all the ACEE projects, the challenges were also plentiful. Because of political opposition, funding was very limited, and additional studies had to be performed to support the value of the advanced turboprop and to identify the most critical technical issues. Areas of technical concern included propeller efficiency at cruise speed, propeller and aircraft interior noise, installation aerodynamics, and maintenance costs.[11]

The development in propulsion technology grew out of the 1973 oil embargo, which had increased fuel costs from about 25 percent of airline direct operating costs to about half. In January 1975, the Senate Aeronautical and Space Science Committee asked NASA to help resolve the fuel crisis. NASA responded with a NASA, Department of Transportation, FAA, and DOD task force that reported on concepts with fuel-saving potential.[12] Among them was an advanced turboprop advocated by NASA's Lewis Research Center and Hamilton Standard Division of United Technologies, the last major propeller manufacturing company in the United States. This design overcame the high-speed compressibility losses of conventional propellers but was controversial because of the perception that using propellers was a return to an outmoded technology.[13] However, the prospect of lower ticket prices was an incentive to accept the new "old" technology.

In 1974, Lewis engineers began evaluating the high-speed turboprop propulsion system to see whether propeller blade redesign might lead to lower fuel consumption. They joined with Hamilton Standard to explore different types of blade shapes intended to allow greater tip speed that would permit propfan-driven aircraft to fly at jetliner speeds while retaining the inherently better fuel consumption found on propeller-driven aircraft.

In 1976, Hamilton Standard performed a series of wind tunnel and other ground tests on an SR-1 (single-rotating) model to investigate how sweep affected propfan performance and noise at speeds of Mach 0.8. The tests resulted in a new type of rotary thruster with extremely thin blades that swept away from the direction of rotation. The researchers conducting the ground tests found that this system could provide jetliner speed at fuel savings of perhaps 30 percent or more if driven by an advanced type of engine.[14] The propfan, as the new concept was called, had eight or more thin, highly swept blades, unlike conventional turboprops, which had up to four straight, large-diameter blades (Figure 3–4).

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[11] Roy D. Hager and Deborah Vrabel, *Advanced Turboprop Project* (Washington, DC: NASA SP-495, 1988), p. 5.

[12] The full name of the task force was the NASA Inter-Center Aircraft Fuel Conservation Technology Task Force, headed by NASA's James Kramer.

[13] John R. Facey, "Return of the Turboprops," *Aerospace American,* October 1988, p. 16. Facey was the advanced turboprop program manager for OAST at NASA Headquarters.

[14] James J. Haggerty, "Propfan Update," *Aerospace,* Fall/Winter 1986, p. 10.

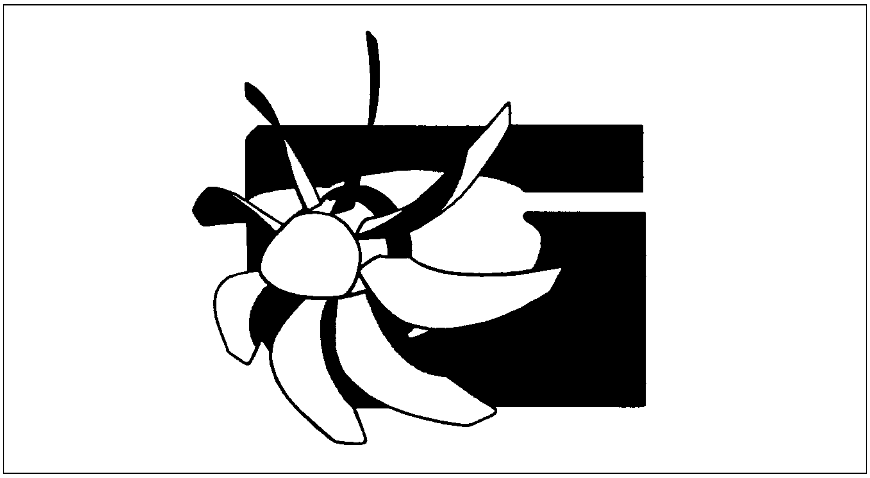

Figure 3–4. The Propfan
(Eight or ten thin, stiff, highly swept turboprop blades allowed speeds comparable to those of subsonic jet transports that were presently in use.)

Between 1976 and 1978, propfan research received only minimal funding. The efforts of a small group of engineers were rewarded, however, in 1978, when the Advanced Turboprop Project formally began, with overall project management at Lewis Research Center. The project's goal was to establish both single- and counter-rotating propfan technologies for Mach 0.65 to 0.85 applications.[15]

The first phase, which lasted through 1980, was called enabling technology. It focused on building subscale propeller models to test and establish the feasibility of the propfan concept. Researchers verified the projected performance, fuel savings, and structural integrity of the different blades under actual operating conditions. They also worked to bring the level of cabin noise and vibration to the point where passenger comfort levels approached those of turbofan-powered airliners. In addition, they verified that propfan-powered aircraft could meet airport and community noise standards as stated in the Federal Air Regulations, Part 36. Hamilton Standard's design studies evaluated the structural characteristics of several large-scale blade configurations. They also conducted preliminary flight research at Dryden to determine propfan source noise using a JetStar aircraft with a powered propeller model mounted above the fuselage and microphones implanted in the airframe.[16]

Other researchers focused on identifying the most suitable configuration for an advanced turboprop aircraft. Two basic installations were tested: the wing-mounted tractor and the aft-mounted pusher (Figure 3–5). The aim was to provide a comprehensive database to assist industry in

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[15] Hager and Vrabel, *Advanced Turboprop Project,* p. v.

[16] NASA report to the House Science and Technology Committee, as reprinted in *Aerospace Daily,* September 8, 1981, pp. 37–38.

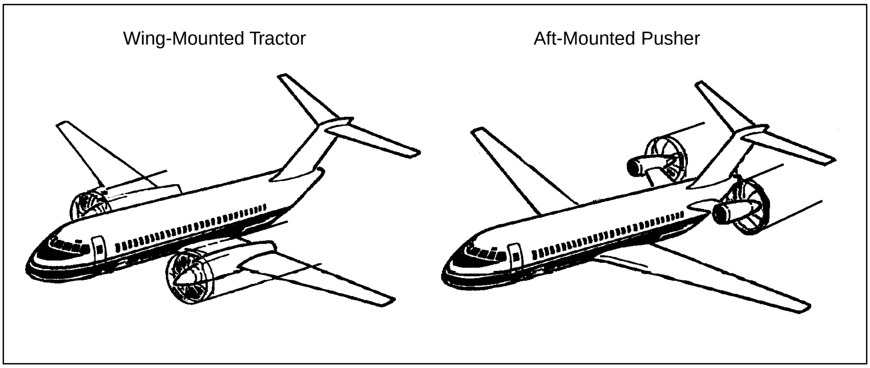

Figure 3–5. Basic Propeller Installation Configurations

choosing a configuration, including whether single- or counter-rotation best suited the application. For an effective installation, the wing and nacelle had to be integrated to avoid drag penalties and aircraft stability and control problems.

The second phase of the Advanced Turboprop Project, called large-scale integration, began in 1981. This phase concentrated on obtaining definitive data on noise at cruise conditions, fuselage noise attenuation, efficient wing mounting, and large-scale blade design. During 1981, NASA and Congress considered accelerating the program in response to strong industry interest. However, this would have required an increase in the total cost of the program, and the goal was abandoned.

In 1981, NASA selected Hamilton Standard to design large-scale, single-rotating propeller assemblies that would be suitable for flight testing. The first phase of the procurement included building a 0.6-meter-diameter aero-elastic propeller model; design and fabrication of a large-scale 2.7-meter-diameter propeller assembly with fixed pitch, ground-adjustable blades; and static and high-speed wind tunnel tests of the large-scale blade assembly. In the second phase of the contract, Hamilton Standard delivered three additional large-scale 2.7-meter-diameter, variable-pitch rotor assemblies that were used for additional static and wind tunnel tests.

During FY 1983 and FY 1984, Congress added $15 million to the amount allocated for the program in anticipation of a contract for the propeller test assembly. In March 1984, NASA selected Lockheed-Georgia Company as the prime contractor, responsible for the overall design of a flight test vehicle and supervision of an industry team that included Hamilton Standard, Allison Gas Turbine Division of General Motors, Rohr Industries, Gulfstream Aerospace Corporation, and Lockheed-California Company. Lewis Research Center was assigned management responsibility for development of the Propfan Test Assessment (PTA) technology effort designed to provide generic data on propfans for dissemination to industry.

In October 1985, before the test assessment program formally began, Lewis tested the new, highly loaded, multi-bladed propellers (called

SR-7A) for use at speeds up to Mach 0.85 and at altitudes compatible with commercial air support system requirements in the Lewis transonic wind tunnel. Using the hardware from an earlier propfan, Hamilton Standard engineers built the first Large-scale Advanced Propfan (LAP) assembly (SR-7L) and tested it at Wright-Patterson Air Force Base in a static propeller test rig they designed and built. Testing of the 2.7-meter-diameter propfan, powered by an electric drive motor in the rig test, began in late August. The propfan assembly completed the test in good mechanical condition. In November 1985, the propeller was shipped to Hamilton Standard to be prepared for the high-speed wind tunnel tests.

High-speed testing was conducted in the S1 wind tunnel at Modane, France. NASA used this tunnel because it was large enough to test the full 2.7-meter-diameter assembly at Mach 0.8 and at 3,658-meter-altitude conditions. The final test series on the SR-7A was performed in the Lewis transonic wind tunnel in early 1987. The tests recorded performance data and completed the high-speed acoustic measurements. The data agreed favorably with predictions and with earlier data.[17]

After static testing was completed under the LAP project, NASA used the SR-7L propfan for further evaluation as part of a complete turboprop propulsion system in the Propfan Test Assessment (PTA) project, under a contract with Lockheed-Georgia. The objectives of this project were to verify the structural integrity of the blading; evaluate the acoustic characteristics of a large-scale propfan at cruise conditions; test the compatibility of the engine, fan, and nacelle; measure propulsion system performance; and acquire data on propulsion system temperatures and stresses.[18]

The PTA project formally began in the summer of 1986 with fifty hours of static testing conducted at a Rohr Industries facility in California. All test objectives were met—the propulsion system functioned according to design, all control systems operated satisfactorily, and the flight instrumentation system operated as planned. Propfan blade stresses and propulsion system temperatures, pressures, and vibrations were within specified limits, and specific fuel consumption was better than expected. The static tests successfully cleared the propulsion system for flight tests.[19]

While NASA was pursuing propfan research in the direction of a single-rotation tractor system, General Electric (GE) Company submitted an unsolicited proposal for a counter-rotation blade concept. In November 1983, Lewis Research Center awarded GE a $7.2 million contract for aircraft propulsion technology research based on modern counter-rotation blade concepts. This approach for a gearless, dual-rotation pusher propulsion system was known as the Unducted Fan, or UDF™. The UDF had two counter-rotating external fans, each with eight sweptback blades

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[17] Hager and Vrabel, *Advanced Turboprop Project,* p. 54.

[18] Haggerty, "Propfan Update," p. 11.

[19] Hager and Vrabel, *Advanced Turboprop Project,* p. 67.

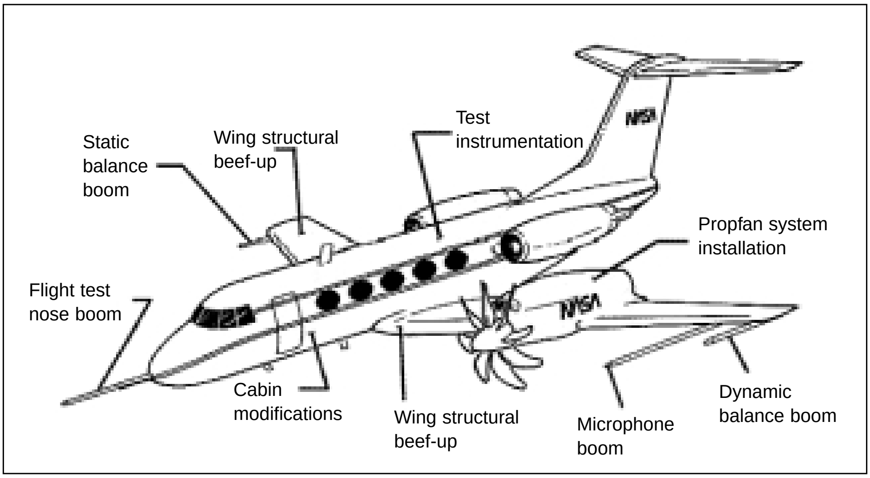

Figure 3–6. Modified Gulfstream II Aircraft Used for Propfan Test Assessment

driven directly by a counter-rotating internal turbine. This gearless design eliminated the weight of a gearbox and its oil cooling system. The UDF had a design rating of 111,200 newtons thrust—a power level intended for commercial transports in the 100- to 160-passenger range.

Model testing began in October 1984 at Lewis and at a Boeing facility. In August 1985, in cooperation with NASA, GE began an extensive ground test program on a full-scale demonstrator engine. The tests, which covered 100 hours and 100 flight cycles, concluded in July 1986. They included successful tests at thrust ratings above the design level and demonstrated a specific fuel consumption rate 20 percent better than for the turbofans then available. Following culmination of the tests on the proof-of-concept engine, GE started assembling a second prototype engine that flew on a McDonnell Douglas MD-80 transport in May 1987. The UDF used 40 to 50 percent less fuel than the engine it replaced. Cabin noise could be kept to less than that of the standard MD-80.[20]

After completing the ground tests, both the LAP and the UDF propulsion systems underwent flight tests. The LAP was tested in a wing-mount installation on a modified Gulfstream II testbed aircraft under a NASA-contracted program with Lockheed (Figure 3–6). Testing took place in May 1987 at Lockheed-Georgia's facility. The UDF was tested as an aft-mounted pusher on a Boeing 727 as part of a GE/Boeing cooperative program. These flight tests began in August 1986 at GE's Mojave, California, test facility. The tests evaluated the structural integrity of the blades and measured the noise both inside and outside the Gulfstream II testbed.

In 1987, three series of flight tests verified the readiness of advanced turboprop propulsion technology for commercial engine systems development. The flight tests included the NASA/GE/Boeing tests of the UDF

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[20] Facey, "Return of the Turboprops," p. 19.

engine on a B-727 aircraft, the NASA/Lockheed PTA of a single-rotation advanced turboprop on a Gulfstream II aircraft, and GE/McDonnell Douglas flight tests of the UDF on an MD-80 aircraft.

NASA continued to work with Lockheed to prove in flight that large, unducted propellers with a radically swept design were a feasible alternative to higher-cost turbofan propulsion systems. Flight tests held in March 1988, at Lockheed facilities in Georgia, examined ways to reduce interior noise levels. Research data were recorded simultaneously for more than 600 parameters using instrumentation such as microphones and accelerometers, strain gauges, temperature, and pressure-measurement gauges.

The final flights in the PTA project were held during May and June 1988. Instruments measured instantaneous pressure on propfan blade surfaces at several flight speeds with a range of power settings on the eight-bladed propfan. After these tests ended, the aircraft were delivered to Johnson Space Center, where the advanced turboprop system was removed and the aircraft modified to a Shuttle training aircraft. The PTA project ended in June 1989.

Other Flight Efficiency Activities

Supercritical Wing/Mission Adaptive Wing. The supercritical wing was a design concept envisioned by Dr. Richard T. Whitcomb, a research engineer at NASA's Langley Research Center, during the 1960s. Whitcomb developed wing shapes that he theorized would make a transonic aircraft much more fuel efficient, either increasing its speed or range or decreasing the amount of fuel it consumed.[21] During the early 1970s, his concepts were tested on an F-8A Crusader at Dryden Flight Research Center.

When increases in the price of oil refocused research efforts more on efficiency than on speed, Whitcomb modified his supercritical wing design for maximum aerodynamic efficiency. The modified wing was one way of improving the lift-drag ratio. The unusual airfoil section controlled the flow over the wing; it avoided the sudden increase in drag that would occur with conventional airfoils operating in high-speed airflow. In addition, it showed this lower drag feature in spite of an increased thickness of the wing section. Consequently, a properly designed supercritical wing reduced wing drag, increased the internal volume for fuel storage, increased the structural efficiency of the wing, and led to lower weight. It showed the potential for fuel savings of 10 to 15 percent, and the design was incorporated into many transport airplanes.

The military also used a supercritical wing on a General Dynamics F-111 aircraft to see how it might benefit military aircraft in its Transonic

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[21] Lane E. Wallace, *Flights of Discovery: 50 Years at the NASA Dryden Flight Research Center* (Washington, DC: NASA SP-4309, 1996), p. 90.

Aircraft Technology (TACT) program, which began in 1972. Test results showed that a supercritical wing could improve aircraft performance. The F-111 TACT kept flying through the early 1980s, testing different drag-reducing aerodynamic modifications.

The C-17 transport, as well as other military transports, also used the supercritical wing. This wing design enhanced the range, cruising speed, and fuel efficiency of the aircraft by producing weaker shock waves that created less drag and permitted high efficiency.[22]

The TACT program provided impetus to further wing research under NASA's Advanced Fighter Technology Integration (AFTI) program. The initial AFTI experiment was the Mission Adaptive Wing (MAW), built by Boeing under a $24 million contract from the Air Force Flight Dynamics Laboratory. The MAW was tested on a modified General Dynamics F-111 TACT aircraft at NASA's Dryden Flight Research Facility. The F-111 AFTI flight research program focused on four automatic modes: cruise camber control, maneuver enhancement/gust alleviation, maneuver camber control, and maneuver load control. It ran from 1985 to 1988.

Internal hydraulic actuators in the MAW flexed the composite-covered aircraft wing to adjust the amount of its camber (curvature), depending on flight conditions. It could flex enough to generate the additional lift needed for slow speeds, eliminating the need for lift-producing devices such as slats and flaps. It could then change to a supercritical wing platform for transonic flight and adjust to a near-symmetrical section for supersonic speeds. The smooth, variable camber wing was expected to yield a 25- to 30-percent improvement in aircraft range and more capability for tight evasive maneuvers. It was also expected to result in increased fatigue life, improved handling, and a more stable weapons platform. Tests indicated that the drag reduction from a MAW design would have 25 percent more range for a low-altitude mission and 30 percent more range for a high-altitude mission. Mission load factors could also be 20 to 30 percent better.[23]

Winglets. Winglets are small, nearly vertical fins installed on an airplane's wing tips to help produce a forward thrust in the vortices that typically swirl off the end of the wing, thereby reducing drag. Whitcomb investigated winglet aerodynamics that matured into an applicable technology. He tested several designs in the wind tunnels at Langley Research Center and chose the best configuration for a flight research program. The concept was demonstrated in flight on a corporate Gates Model 28 Longhorn series Learjet and further tested on a large DC-10 aircraft as part of the ACEE program.

NASA installed winglets on a KC-135A tanker, on loan from the Air Force, and flight-tested it at Dryden Flight Research Center in 1979 and

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[22] "NASA Contributions to the C-17 Globemaster III," *NASA Facts,* FS-1996-05-06-LaRC (Hampton, VA: Langley Research Center, May 1996).

[23] Remarks by Louis Steers, director of NASA's MAW effort, speaking at an industry briefing session on the AFTI/F-111 program, printed in *Antelope Valley Press,* August 4, 1988.

1980. The research showed that the winglets could increase an aircraft's range by as much as 7 percent at cruise speeds. The first industry application of the winglet concept was in general aviation business jets, but winglets were also incorporated into most new commercial and military transport jets.[24]

Laminar Flow Research. One problem for modern civil air transports traveling at about 800 kilometers per hour occurs in the boundary layer, a thin sheet of flowing air that moves along the surfaces of the wing, fuselage, and tail of an airplane. At low speeds, this layer follows the aircraft contours and is smooth—a condition referred to as "laminar." At high speeds, the boundary layer changes from laminar to turbulent, creating friction and drag that wastes fuel. It was estimated that the maintenance of laminar flow over the wing and tail surfaces of long-range transports could reduce fuel consumption by 25 percent or more. Researchers developed three methods for increasing laminar flow and controlling the behavior of laminar/turbulent boundary layers:

1. Natural laminar flow, which reduced skin-friction drag by shaping and passive control
2. Laminar flow control and hybrid laminar flow control, which reduced skin-friction drag by combined shaping and active control
3. The development of low Reynolds-number airfoils, which reduced pressure drag by shaping with and without passive or active control.[25]

NASA conducted natural laminar flow experiments on the variably swept-wing F-111 during the late 1970s. These experiments investigated how changing the sweep of a wing affected the degree of its laminar flow. Research in the early 1980s, using a Navy Grumman F-14 Tomcat, investigated sweep angles greater than those found on the F-111. This research told investigators how much sweep could be incorporated into a subsonic wing before it began to lose its laminar flow properties.[26]

The laminar flow control concept called for maintaining laminar flow by removing the turbulent boundary layer by suction (Figure 3–7). Suction required developing porous or slotted aircraft surfaces and lightweight pumping systems.[27] The concept had been well established,

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[24] Wallace, *Flights of Discovery,* p. 93.

[25] William D. Harvey, Head, Fluid Dynamics Branch, Transonic Aerodynamics Division, NASA Langley Research Center, "Boundary-Layer Control for Drag Reduction," paper presented at the First International Pacific Air and Space Technology Conference, Melbourne, Australia, November 1987, pp. 2, 9. The Reynolds number is a ratio used to calculate flow characteristics; it is useful in characterizing a flow in a simulated environment, such as a wind tunnel.

[26] Wallace, *Flights of Discovery,* p. 95.

[27] "Aircraft Energy Efficiency Program: Laminar Flow Control Technology," *NASA Facts,* NF-86/8-79 (Washington DC: U.S. Government Printing Office, 1979).

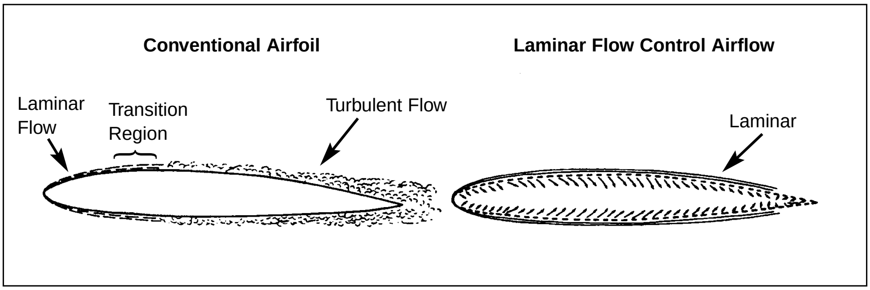

Figure 3–7. Laminar Flow Control Through Suction

verified in wind tunnel tests, and demonstrated in various flight tests, particularly the X-21 flight research program performed by the Northrop Corporation in the 1960s under an Air Force contract. This program demonstrated that under controlled conditions, laminar flow could be established and maintained over essentially the entire wing surface where suction was applied. The Laminar Flow Control Project, which began in 1976, demonstrated that the technology was ready for practical application to commercial transports during the next decades. Figure 3–8 shows some of the concerns regarding the implementation of laminar flow control on a typical aircraft.

The program continued in the early 1980s, and researchers at Langley Research Center predicted that modern construction techniques would allow full-size wings to be built that approached the smoothness of highly accurate wind tunnel scale models and flight test wings. During 1982,

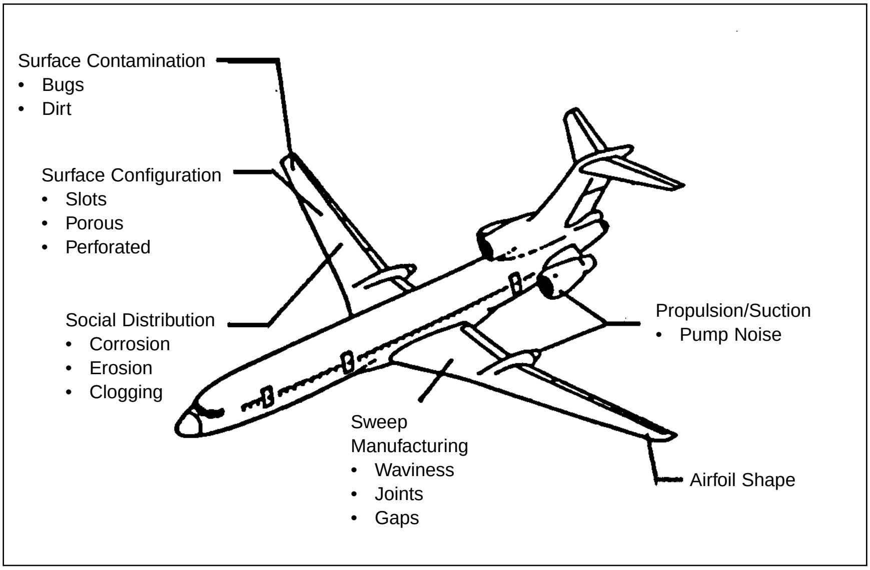

Figure 3–8. Factors Affecting Laminar Flow
(Bugs and dirt can contaminate the surface. Corrosion, erosion, and clogging can affect the airflow through the tiny slots. Manufacturing irregularities can reduce the effectiveness of the system.)

flight tests at Langley substantiated those predictions. The aircraft had either bonded wing skins made of aluminum, integrally stiffened milled skins of aluminum, or skins made of composites. The research also provided data on the effect of other factors on subsonic laminar flow, such as aircraft speed and insects being splattered on aircraft wings. The researchers found that wherever insects hit and stuck to the surface of the aircraft, they interfered with the smoothness of the boundary layer of air.

In 1985, NASA installed two experimental laminar flow control devices on its business-size JetStar aircraft that incorporated techniques to help prevent leading-edge contamination—that is, disturbance of the laminar flow by insects, ice, and other obstructions adhering to the leading edges of an aircraft's wings. The flights took place in widely separated areas of the United States to experience a wide variety of contaminant conditions.

Following this research, in September 1987, NASA selected Boeing to provide data on the aerodynamic and operational effectiveness of a hybrid system to achieve laminar airflow control at flight conditions representative of high subsonic speeds of commercial and military transport airplanes. During the three-year program, designers developed a shield for use while an aircraft was close enough to the ground to encounter insects, ordinarily within 300 meters of the ground. This shield, called a Krueger flap, folded flush against the wing's lower surface when not in use, but when extended forward and upward, it became the leading edge of the wing—the part that encountered the insects. On a Boeing 757 used to demonstrate the flap, the suction system used with the flap not only created laminar flow over the leading part of the wing but also demonstrated that laminar flow continued behind it to cover 65 percent of the distance to the trailing edge.

Beginning in the late 1980s, NASA started examining laminar flow on aircraft traveling at supersonic speeds. NASA acquired two F-16XL aircraft and began research flights at Dryden Flight Research Center in 1991 in a joint activity with Rockwell.

Riblets. Riblets also reduce drag-producing air turbulence and increase fuel efficiency. Investigators at Langley Research Center discovered in 1984 wind tunnel experiments that barely visible grooves, each shaped like a tiny "v," on the surface of an airplane, no more than two-thousandths of an inch deep, would favorably alter the turbulent flow of air that formed over the surface of a moving airplane. The 3M Company used this technology to design and produce test specimens of riblets in tape form with an adhesive backing that would be pressed into place on an aircraft's surface.

Oblique Wing Research. NASA's oblique wing research successfully demonstrated an aircraft wing that could be pivoted obliquely from zero to sixty degrees during flight. The wing was demonstrated on a small subsonic jet-powered research aircraft called the AD-1 in a program conducted between 1979 and 1982. The first sixty-degree angle skew was reached on its twenty-third flight on April 24, 1981.

The oblique wing concept originated in 1945 with Robert T. Jones, at NASA's Ames Research Center, but the idea was not pursued until the late 1960s. Analytical and wind tunnel studies indicated that a transport-size oblique wing flying at 1,600 kilometers per hour might achieve twice the fuel economy of more conventional wings.[28] The studies stated that, at high speeds, pivoting the wing up to sixty degrees would decrease aerodynamic drag, permitting increased speed and longer range with the same fuel expenditure. At lower speeds, during takeoffs and landings, the wing would be perpendicular to the fuselage like a conventional wing to provide maximum lift and control qualities. As the aircraft gained speed, the wing would be pivoted to increase the oblique angle, thereby reducing the drag and decreasing fuel consumption.[29]

NASA demonstrated the concept on the AD-1 aircraft, which was delivered to Dryden Flight Research Center in February 1979. During seventy-nine flights that took place over eighteen months, the wing was pivoted incrementally until the full sixty-degree angle was reached in 1981. The aircraft continued to be flown for another year, obtaining data at various speeds and wing pivot angles until the final flight in August 1982. Although successful, the concept had not been incorporated into any production aircraft at the time this volume went to press.

NASA began a follow-up program to the AD-1 in the early 1980s. The goal of the program was to modify the NASA F-8 digital fly-by-wire research aircraft to a supersonic oblique wing configuration. In 1983, researchers completed a feasibility study of the oblique wing concept operating at supersonic speeds. In November 1984, NASA solicited proposals for the preliminary design phase of a joint NASA-Navy program to design, construct, and evaluate an oblique wing during supersonic flight research conditions. The solicitation marked the second phase of a planned four-phase program that was also to define the aircraft's expected flight performance and determine the potential operational capabilities for Navy applications. Phase 3 was to include detailed design work, fabrication, and ground testing of a composite, aero-elastically tailored oblique wing. The composite wing was to be constructed so that the bending stresses of flight would not degrade the wing's aerodynamic efficiency. Phase 4 was to consist of a flight support contract to the Phase 3 contractor. A twelve-month, approximately forty-flight test program was planned to take place in 1986 and 1987 from Dryden.[30]

Rockwell received the contract for the design work. However, the work did not progress beyond the design stage. The Navy canceled the program near the end of the second phase just before the modifications were set to begin, and the modifications to the F-8 never took place.

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[28] Wallace, *Flights of Discovery,* p. 94.

[29] "The AD-1," *NASA Facts On-Line,* Dryden Flight Research Center, November 1994.

[30] "NASA Seeks Design for Supersonic Oblique Wing Testbed," *Aviation Week & Space Technology,* December 3, 1984.

Powered Lift Technology. Powered lift enables aircraft to operate from short or reduced-length runways because the aircraft can take off and land vertically or after traveling only a short distance on the ground. Variations of this technology include short takeoff and landing (STOL), vertical takeoff and landing (VTOL), vertical/short takeoff and landing (V/STOL), and short takeoff and vertical landing (STOVL) aircraft. Most of these technologies appeared on some variation of rotorcraft. However, the QSRA and the C-17 Globemaster III also incorporated STOL technology.

The subsonic STOL aircraft's enhanced in-flight capabilities include steep-gradient and curved-flight departures and approaches, high rates of climb, steep final descents, high maneuverability, rapid response for aborted landing, and low landing approach airspeeds. These characteristics allow for aircraft that:

- Require less airspace in the near-terminal area
- Require less ground space at the terminal
- Operate in smaller spaces relatively quietly
- Have improved crashworthiness and survivability because of their low-speed capability at near-level fuselage attitudes
- When equipped with modern avionics, can operate in very low visibility in adverse weather[31]

These aircraft are useful in both civilian and military situations. STOL concepts investigated by NASA included the augmentor wing and the upper-surface-blown flap and research with the four-engine QSRA.

Quiet Short-haul Research Aircraft. The QSRA originated as a proof-of-concept vehicle and a research tool. It was designed to demonstrate new forms of lift that researchers believed might one day be used in commercial and STOL aircraft. It validated the technology of a propulsive lift system that used upper-surface blowing.

The QSRA program began in 1974. NASA obtained an aircraft and several high-bypass-ratio geared engines at no cost for use in the program. Boeing assembled the aircraft, and rollout occurred on March 31, 1978. The initial flight testing for airworthiness took place at Boeing, and the aircraft was then delivered to Ames Research Center in August 1978, where a flight evaluation was conducted.

The high-performance STOL characteristics resulted from its new moderately swept wing, designed and built by Boeing. It incorporated the upper-surface-blowing propulsive-lift technique in its design. Four acoustically treated jet engines were mounted on top of the wing so that the fan air from the engines was directed across the upper

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[31] W.H. Deckert and J.A. Franklin, Ames Research Center, *Powered-Lift Aircraft Technology* (Washington, DC: NASA Office of Management, Scientific and Technical Information Division, 1989), p. 3.

surface of the wing and flaps to create very high levels of lift as compared to conventional wings. The design gross weight of the aircraft was 22,700 kilograms. Even with four turbofan engines, it could operate at lower noise levels than most current small business jet airplanes—an attractive feature.

In June and July 1980, NASA and the U.S. Navy used the QSRA for more than 500 landings on a simulated aircraft carrier deck in an investigation of the application of propulsive-lift technology to aircraft carriers. This was followed by the initiation of a joint NASA-Navy program that used the QSRA to evaluate the application of advanced propulsive-lift technology to naval aircraft carrier operations. This consisted of thirty-six “touch and go” landings and sixteen full-stop landings and takeoffs. The aircraft demonstrated new technology for quieter jet engine operations while also providing the performance for operations from airports with very short runways. The QSRA also successfully completed a forty-three-flight evaluation program in January 1981, at Ames Research Center, where test pilots made short runway landings with malfunctions in the aircraft that were intentionally created.

The Quiet, Clean, Short-haul Experimental Engine (QCSEE) was a related development. Test runs began at Lewis Research Center in the late 1970s. The goal of the program was to produce a power plant for a four-engine 150-passenger STOL transport with a small and relatively low noise footprint. The STOL technology around which NASA developed the QCSEE used the engine exhaust to produce lift. In one case, the exhaust was blown directly over external flaps to produce the added lift for STOL. In the other, part of the bypass air was ducted to blow over the upper surface of the wing to generate additional lift. Both of these engine types were built and successfully tested.

C-17 Globemaster III. The first C-17 Globemaster III rolled off the assembly line in 1991—the culmination of a lengthy process that began in 1979 when DOD began its Cargo-Experimental program. In 1981, the Air Force selected McDonnell Douglas as the manufacturer of the aircraft. The company used NASA-derived technologies to produce the aircraft.

The aircraft used a powered lift system, or “externally blown flap,” that enabled the aircraft to make slow, steep approaches with heavy cargo loads. The steep approach helped pilots make precision landings. This was accomplished by diverting engine exhaust downward, giving the wing more lift. In this system, the engine exhaust from pod-mounted engines impinged directly on conventional slotted flaps and was deflected downward to augment the wing lift. This allowed aircraft with blown flaps to operate at roughly twice the lift coefficient of conventional jet transport aircraft. Researchers studied the concept extensively in wind tunnels at Langley Research Center, including tests of flying models in the nine-meter by eighteen-meter tunnel. The Air Force procurement specification included a STOL capability. Researchers investigated this capability on flight simulators and the Augmentor Wing Research Aircraft at Ames Research Center.[32]

Subsonic V/STOL applied concepts that used a lifting rotor, a tilt-rotor, and the X-wing configuration. The military used subsonic V/STOL technology in its Harrier aircraft. Civil opportunities for subsonic V/STOL aircraft included:

- Ocean resource operations, with "terminals" on oil rigs, ships, and mineral exploration platforms
- Direct city center to city center transportation
- Direct corporate office to factory service
- Transportation for underdeveloped countries
- Transportation for inaccessible communities
- Search and rescue
- Emergency medical services
- Disaster relief

NASA used its National Full-Scale Aerodynamics Complex wind tunnels at Ames Research Center to determine the low- and medium-speed aerodynamic characteristics of high-performance aircraft, rotorcraft, and fixed-wing powered-lift V/STOL aircraft.

Powered Lift Rotorcraft Research. NASA and DOD also developed several rotary-wing-based aircraft that used powered lift technology. These included the XH-59A, advancing blade concept aircraft during the 1970s, the JVX or tilt-rotor aircraft, and the RSRA/X-wing aircraft. These aircraft had the common ability to take off and land vertically like a helicopter, but in flight, they used a variety of technologies to operate as conventional fixed-wing aircraft.

Rotor Systems Research Aircraft/X-Wing Program. Jointly funded by NASA and the U.S. Army, the RSRA aircraft program began in the early 1970s. The program investigated ways to increase rotor aircraft speed, performance, reliability, and safety and to reduce helicopter noise, vibration, and maintenance. There were two aircraft in the program manufactured by Sikorsky Aircraft Division, United Technologies Laboratories, for Langley Research Center. After initial flight testing at Langley, the two aircraft were transferred to Ames Research Center for an extensive flight research program by Ames and the Army.

The RSRA could be configured to fly as a helicopter or as a compound helicopter and could be fitted with a variety of experimental and developmental rotor systems for research purposes. The compound configuration had fixed wings providing a portion of the needed lift and auxiliary jet engines; it could accommodate rotor systems too small to support the aircraft. Table 3–62 compares the helicopter and compound configurations.

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[32] "NASA Contributions to the C-17 Globemaster III."

A unique rotor vibration isolation system prevented the transmission of main rotor vibrations to the fuselage structure. This allowed for the installation of various rotor systems with a wide range of vibration characteristics without modifying the fuselage. At the same time, the system provided precise measurements and control of rotor forces and of aircraft maneuvering flight parameters over a wide range of operating conditions.[33]

NASA and DARPA initiated a follow-up program to investigate the X-wing concept. Sikorsky was selected in early 1984 to work with NASA and DARPA on converting one of the two RSRAs to a demonstrator aircraft for the X-wing concept. It was envisioned that the four-blade X-wing would operate like a standard helicopter rotor for vertical and low-speed flight, but could be stopped and function as a wing for high-speed forward flight. It was expected that X-wing technology would lead to rotorcraft that could operate at greater speeds and altitudes than existing helicopters.[34]

The modified RSRA airframe could be configured in three flight modes: fixed wing (airplane), helicopter, and compound. In the compound mode, the RSRA could transition between fixed-wing and helicopter configurations. For fixed-wing configuration taxi and flight testing, the tail rotor would remain in place, attached to the rudder pedals for yaw control. The main rotor system would be removed. In the helicopter configuration (X-wing), twin GE T58–GE-5/100 gas turbine engines powered the rotor system.[35]

One of the two RSRA Sikorskys was designated an X-wing demonstration aircraft under the contract with Sikorsky. The second RSRA was based at Dryden for fixed-wing configuration testing, which began on May 8, 1984. This marked the first time the RSRA in the compound configuration was flown in the airplane mode. The tests were conducted with the RSRA equipped with its tail rotor but no main rotor and test speeds limited to less than 463 kilometers per hour and also with the RSRA completely rotorless for higher speed flights. Tests were carried out at altitudes up to 3,000 meters. A total of thirteen tests were conducted.

The modified RSRA with the X-wing system mounted on it was rolled out on August 19, 1986, at Sikorsky's facilities in Connecticut. Although researchers did not foresee replacing conventional fixed-wing or rotorcraft with the X-wing aircraft, they envisioned that X-wing aircraft would provide enhanced capabilities to perform missions that called for the low-speed efficiency and maneuverability of helicopters combined with the high cruise speed of fixed-wing aircraft. The aircraft had a 13.7-meter, variable-incidence conventional wing that could support the full weight of the aircraft in flight. The aircraft

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[33] "Advanced Research Aircraft," NASA Activities, May 1979, p. 11.

[34] "X-Wing Contract," *Aviation Week & Space Technology,* January 2, 1984, p. 23.

[35] "NASA Nears Fixed-Wing Tests on RSRA Research Aircraft," *Aviation Week & Space Technology,* January 30, 1984, p. 54.

was expected to demonstrate convertibility from rotary to wing-borne flight and to efficiently combine the vertical lift and stable hover characteristics of conventional helicopters with the high cruise speed of fixed-wing aircraft.[36]

The aircraft was twenty-one and a half meters long by five and a half meters high and had a five-blade tail rotor just over three meters in diameter. The design gross weight was 15,093 kilograms. Power for the X-wing/RSRA rotor came from two T58-GE-10 engines. Two TF34-GE-400As provided thrust for forward flight.[37]

The X-wing used a four-bladed helicopter-like rotor system that would rotate for takeoffs, landings, and low-speed flight. The rotor system would be stopped in flight at speeds of approximately 281 to 370 kilometers per hour to act as a fixed x-shaped wing for high-speed flight. In the x-shape, two blades would be swept forward at forty-five-degree angles, and two would be swept to the rear at the same angles. The prime objective of the program was the successful demonstration in flight of conversion of the rotor-wing system from fixed to rotating and back again.

A computer-controlled air-circulation control system would provide lift. It would first be used with the X-wing not rotating and then rotating. As testing proceeded, rotor turning and circulation control development would enable researchers to gradually achieve more lift with the rotor rather than depending on the aircraft fixed wing. Advanced composite materials were used in the four-rotor/wing blades.[38]

Plans called for the RSRA/X-wing aircraft to be flown in the fall of 1986 first as a fixed-wing aircraft without the rotor and then with the X-wing installed in a fixed position. The next phase would include full operation of the X-wing blowing systems, with the rotor stationary in normal horizontal flight. Ground testing of the X-wing in rotary mode would follow, and then conversion test flights between rotary and horizontal flight modes would complete the program. However, the tests were delayed by a series of technical problems linked to design changes and the extensive reassembly required after the aircraft was shipped from Sikorsky in Connecticut to Edwards Air Force Base in California.

The delays and cost overruns led NASA and DARPA to scale down the X-wing flight test program in August 1987 to a low-level research effort that concentrated on basic research objectives and postponed the demonstration of conversion from rotary to fixed-rotor flight modes. The conversion demonstration would have required the development of complex digital computers and software, and developing the flight hardware

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[36] “NASA/DOD Hybrid Research Aircraft Rolled Out,” *NASA News,* Release 86-113, August 19, 1986.

[37] “Sikorsky Rolls Out X-Wing Demonstrator,” *Aviation Week & Space Technology,* August 25, 1986, p. 19.

[38] “X-Wing Research Aircraft Set for Delivery to NASA,” *NASA News,* Release No. 86-13, September 18, 1986.

for the X-wing concept proved to be far more complex than was first thought.[39]

Initial flight tests were made in November and December 1987 without the X-wing rotor. The flights evaluated the basic stability of the aircraft in the first of three rotor-off configurations. The contract with Sikorsky ended in December 1987. Further flight tests and modification work on the X-wing RSRA were halted in January 1988 while NASA and DARPA assessed the program's future.

JVX/Tilt-Rotor. The JVX/tilt-rotor program was NASA's second primary research effort involving rotorcraft. NASA contributed to the JVX program through the transfer of generic tilt-rotor technology. NASA also provided facilities and expertise to address technology issues specific to the JVX.[40]

Tilt-rotor aircraft operated as helicopters at low speeds and as fixed-wing propeller-driven aircraft at higher speeds. This permitted vertical takeoff and landing, longer cruising range, and speeds up to 640 kilometers per hour (as compared to conventional helicopters, which were limited to less than 320 kilometers per hour).

Concepts for tilt-rotor VTOL aircraft had been first studied in the late 1940s, and related investigations continued into the 1970s. During the early 1970s, the joint NASA-Army XV-15 Tilt Rotor Research Aircraft (TRRA) program began. This aircraft, developed by Bell Helicopter Textron, was a third-generation tilt-rotor V/STOL aircraft. The 12.8-meter long, 5,900-kilogram craft was powered by two 1,120-kilowatt turbine engines located in the wing tip nacelles that rotate with the rotors. The XV-15 was the first research aircraft with rotors that were designed to be tilt rotors. The XV-3 that had been designed earlier had helicopter-designed rotors that could be tilted.

By the early 1980s, tests with the XV-3 and XV-15 research aircraft and other supporting research had proven that the critical design issues could be successfully addressed. The joint NASA-Army TRRA program provided the confidence level necessary for DOD to initiate full-scale development of the JVX. The V-22 Osprey was the designation for the military version of the JVX (Figure 3–9). It was based on the Bell XV-15 tilt-rotor demonstrator.

Scale-model wind tunnel testing was conducted at Langley Research Center to investigate JVX spin characteristics and to establish aeroelastic stability boundaries for the JVX preliminary design. The Vertical Motion Simulator at Ames Research Center was used in two design and development tests to validate the JVX math model and evaluate the flight control system characteristics. Critical performance testing completed at the Ames Outdoor Aerodynamic Research Facility provided new data on hover efficiency and wing download.[41]

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[39] "Technological Problems, Rising Costs Force X-Wing Program to Scale Down," *Aviation Week & Space Technology,* October 19, 1987, p. 23.

[40] William S. Aiken, Jr., NASA Director for Aeronautics, to Lynn Heninger, memorandum, July 9, 1985.

[41] *Ibid.*

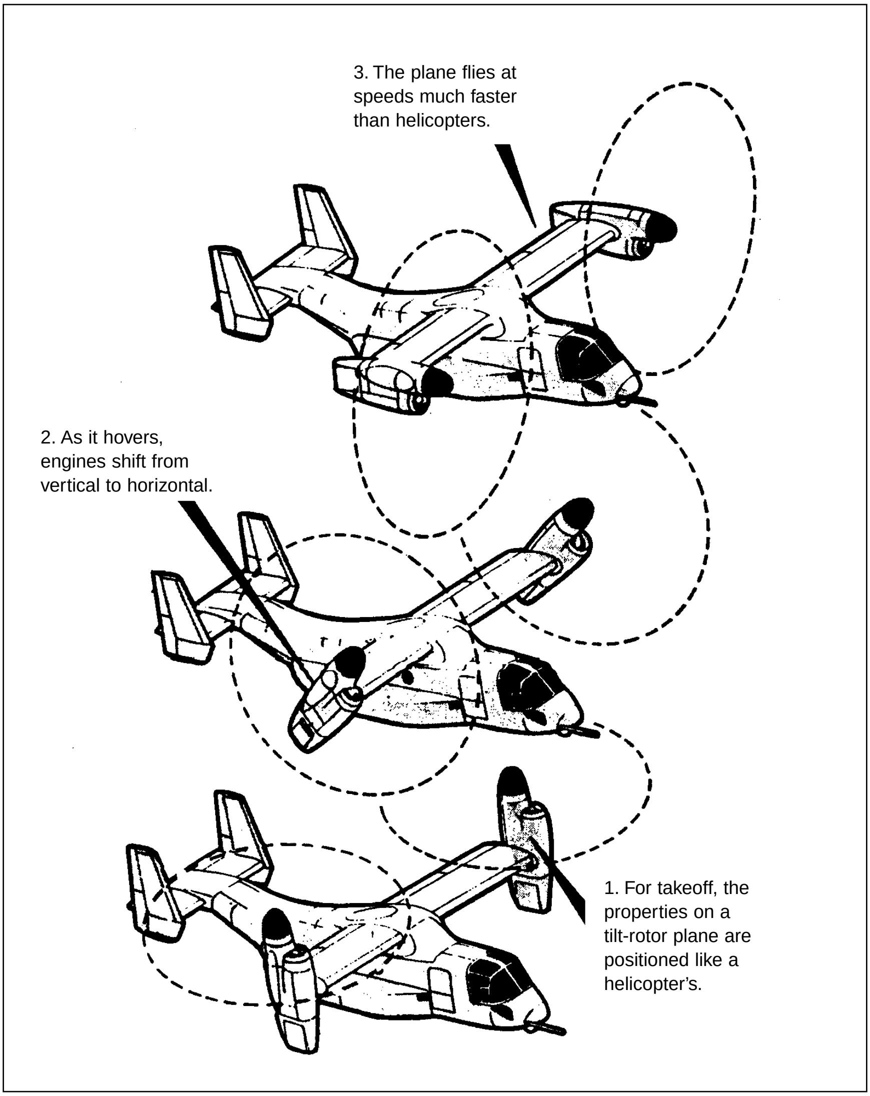

Figure 3–9. Tilt-Rotor Aircraft

NASA also provided in-house expertise, analysis routines, and basic research. Langley researchers provided improved analytical methods to industry and worked closely with the contractors to analyze the JVX wing/rotor aero-elastic coupling characteristics. They gave similar assistance in composite construction, flying qualities, performance, engine inlet design, and rotor dynamics. NASA developed computer programs that continued to be used by Bell and Boeing to make key design choices. Basic research tasks included airfoil design for an advanced technology rotor, crashworthiness concepts, fatigue analysis, cockpit integration, and an XV-15 flight evaluation of side-arm controllers.

The tilt-rotor concept had civil potential because of its VTOL- and STOL-mode capabilities, fuel efficiency, and low noise and vibration levels. An effort was made to fund a civilian version of the JVX that would enable passengers to board at special facilities near city centers and fly into the center of another city, saving commuting time and reducing congestion at major commercial airports. However, the cost was too high. The FAA estimated that a tilt-rotor aircraft built to carry thirty passengers would cost between $15 million and $19 million—two to five times the price of a comparably sized turboprop.

A related research program initiated by NASA included the design, fabrication, and flight evaluation of advanced technology blades (ATB), known as the SV-15/ATB program. Program objectives were to improve the SV-15's VTOL performance, expand the conversion envelope between helicopter and airplane modes of flight, and at least maintain cruise propulsive efficiency. The results from static (hovering) tests of the isolated-full-scale ATB rotor verified theoretical predictions. The first flight of the XV-15/ATB was in late 1987.

The objective of another XV-15 research program was to establish the viability of a three-axis sidearm controller as a primary controller for tilt-rotor aircraft. The first flight with the sidearm controller occurred in June 1985. Ongoing research with the XV-15 included support for the V-22 Osprey tilt-rotor program, flight evaluation of new tilt-rotor steel hubs, and more complete determination of rotor downwash characteristics, documentation of handling qualities, and STOL performance.

Advanced Short Takeoff and Vertical Landing (ASTOVL). The ASTOVL program was a cooperative research effort between the United States and the United Kingdom. NASA, DOD, and the United Kingdom signed a memorandum of understanding in February 1986 to proceed with a research program to investigate various propulsion concepts. The program would assess the relative potential as well as the joint research required for advancement of these technologies to future ASTOVL aircraft. The program aimed to reduce the technological risk associated with potential future ASTOVL combat aircraft. Those aircraft would have the capabilities of an advanced supersonic fighter aircraft with the added advantage of landing vertically when necessary.

NASA awarded contracts to Allison, General Electric, and Pratt & Whitney to evaluate the four propulsion concepts. NASA and DOD also awarded contracts to study airframe design to General Dynamics, Grumman, Lockheed, and McDonnell Douglas. British participants included British Aerospace and Rolls Royce. Reviews of the four concepts were held late in 1987 and in 1988. Remote augmented lift systems and ejector augmentors were selected for further studies early in 1989.

Aircraft Control With Computerized Aircraft Systems. The digital fly-by-wire (DFBW) system replaced conventional mechanical flight controls with an electronic flight control system that was coupled with a digital computer. It allowed the control surfaces of an aircraft to be operated electronically through a computer system. The pilot would move the aircraft's stick, which sent a command to the flight control computer. The computer would calculate the necessary control surface movements and send a command to the actuator to move the control surfaces. The development and early tests of the system occurred during the 1970s.

Draper Laboratory, which had developed an extensive software development process for the Apollo program, developed the flight-critical software for the DFBW program. Dryden engineers, in turn, adapted Draper's methods to develop all the subsequent flight control system software used at the center.[42]

The first DFBW flight occurred in May 1972, using an F-8C research aircraft and a single Apollo digital computer with an analog backup. This phase of the DFBW program validated the fly-by-wire concept and showed that a refined system—especially in large aircraft—would greatly enhance flying qualities by sensing motion changes and applying pilot inputs instantaneously.

Phase II of the program began in 1973. During this phase, developers replaced the Apollo hardware with a triply redundant digital computer system, the IBM AP 101, which would be more like a system that industry would use and which was also selected for the Space Shuttle control system. Computer synchronization, redundancy management, and the demonstration of data bus concepts that reduced the amount of hard-wiring necessary in the control system were also developed during Phase II of the DFBW program.[43]

The F-8 was also used both to get the "bugs" out of the AP-101 computer and to remedy a problem that pilots encountered on the fifth approach and landing test of the unpowered Space Shuttle *Enterprise* in October 1977. Pilot-induced oscillation can occur on computerized control system aircraft because the linkage is no longer direct between the pilot's control stick and the control surfaces. This results in a greater possibility that the pilot's input and the aircraft's response will become unsynchronized. The human tendency is to respond to what is seen, and a pilot's actions can "fight" an aircraft's control system, causing overcontrol and unplanned movement, sometimes at a dangerous level.

When the problem appeared during the approach and landing test, NASA scheduled an additional series of test flights with the F-8 and other aircraft to try to replicate the problem and experiment with solutions. These tests occurred in March and April 1978 and provided needed data to develop a solution, a P10 suppression filter.[44] The Shuttle was launched beginning in 1980, using DFBW for descent, approach, and landing maneuvers and experiencing a perfect safety record in this part

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[42] Wallace, *Flights of Discovery,* p. 114.

[43] *Ibid.,* p. 115.

[44] James Tomayko, "Digital Fly-by-Wire: A Case of Bidirectional Technology Transfer," *Aerospace Historian,* March 1986, pp. 15–18.

of the flight. In 1978, the F-18 Hornet became the first production DFBW aircraft.[45]

Farther into Phase II, in August 1984, the F-8 aircraft was given resident backup software technology designed to tolerate errors in its digital control system without the use of analog or hardware backup. Early flight tests were successful.

The DFBW program lasted 13 years. The 210th and final flight of the program took place on April 2, 1985. The F-8 program proved the feasibility of DFBW aircraft and gave the technology enough credibility to encourage industry to incorporate computerized flight control systems in new aircraft designs, such as the later models of the F-16 and the Boeing 777.[46]

Throughout the 1980s, researchers continued to improve and use DFBW technology. The X-29 high-performance research aircraft, flown from 1984 through 1992, used DFBW technology in its flight control system to sense flight conditions (including aircraft attitude, speed, and altitude), to process this information, and to continually adjust the control surfaces, transmitting up to fifty commands a second to provide artificial stability for the aircraft, which had an inherently unstable design. The X-29 used a triply redundant three-computer digital system, each with analog backups. If one digital system failed, the remaining two would take over. If two digital computers failed, the flight control system would switch to the analog mode. If one of the analog computers failed, the two remaining analog computers would take over. The risk of failure in the X-29's system was less than the risk of a mechanical failure in a conventional system. The digital system allowed relatively easy software changes to modify the "control calculations" or control laws to suit research needs or changing flight conditions.

Research during the 1970s on the Integrated Propulsion Control System, which used a General Dynamics F-111E, led to flight research with an advanced digitally controlled engine designed by Pratt & Whitney. This engine, with the Digital Electronic Engine Control (DEEC) system, was installed on Dryden's F-15 and flown from 1981 to 1983. The DEEC engines allowed engine stall-free performance throughout the entire F-15 flight envelope, faster throttle response, improved air-start capability, and an increase of 305 meters of altitude in afterburner capability.[47]

A follow-up effort to DEEC research mixed a digital jet engine control system, a mated digital flight control system, an on-board general-purpose computer, and an integrated architecture that allowed all components to communicate with each other. A modified F-15 jet aircraft performed the first flight of the Highly Integrated Digital Electronic

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[45] Wallace, *Flights of Discovery,* p. 116.

[46] *Ibid.*

[47] *Ibid.*, p. 120.

Control (HIDEC) system on June 25, 1986, from Dryden. It marked the first time such large-scale integration efforts were attempted in aircraft systems. The HIDEC F-15 also had a dual-channel, fail-safe digital flight control system programmed in Pascal. It was linked to the Military Standard 1553B and an H009 data bus that tied all other electronic systems together. The HIDEC technology permitted researchers to adjust the operation of the engines to suit the flight conditions of the aircraft. This extended engine life, increased thrust, and reduced fuel consumption. HIDEC also added flight control information such as altitude, Mach number, angle of attack, and sideslip. The HIDEC system actively adapted to varying flight conditions, allowing the engine to operate closer to its stall boundary to gain additional thrust.

The Advanced Digital Engine Control System (ADECS) also used the F-15. This system traded excess engine stall margin for improved performance that was achieved through the integrated and computerized flight and engine control systems. The engine stall margin—the amount that engine-operating pressures must be reduced to avoid an engine stall—was continually monitored and adjusted by the integrated system, based on the flight profile and real-time performance needs.

Using this information, ADECS freed up engine performance that would otherwise be held in reserve to meet the stall margin requirement. Improved engine performance obtained through ADECS could take the form of increased thrust, reduced fuel flow, or lower engine operating temperatures because peak thrust was not always needed.

The initial ADECS engineering work began in 1983. Research and demonstration flights with ADECS began in 1986. These flights displayed increases in engine thrust of 10.5 percent and up to 15 percent lower fuel flow at constant thrust. The increased engine thrust observed with ADECS improved the aircraft's rate of climb 14 percent at 12,192 meters, and its time to climb from 3,048 meters to 12,192 meters was reduced 13 percent. Increases of 14 percent and 24 percent, respectively, in acceleration were also experienced at intermediate and maximum power settings. No stalls were encountered during even aggressive maneuvering, although intentional stalls were induced to validate ADECS methodology.[48]

High-Performance Aircraft

High-performance aircraft technologies were generally developed to support military objectives. DOD— and particularly its research arm, DARPA—often generated these efforts and usually also contributed at least part of the funds. However, because NASA had a hand in the technology development, the technologies were sometimes also transferred to

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[48] "F-15 Flight Research Facility," *NASA Facts On-Line,* FS-1994-11-022-DFRC, Dryden Flight Research Center, November 1994.

the civilian sector. An example was the X-29 aircraft. Its technologies were developed and intended for both civilian and military aircraft.

HiMAT

The HiMAT (Highly Maneuverable Aircraft Technology) subscale research vehicles flown from Dryden from mid-1979 to January 1983 demonstrated advanced fighter aircraft technologies that could be used to develop future high-performance military aircraft. Two vehicles were used in the research program that was conducted jointly by NASA and the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base in Ohio. The North American Aircraft Division of Rockwell International built the vehicles.

The two HiMATs were equipped with different instrumentation but had identical fundamental designs. The first aircraft was configured to fly at transonic and supersonic speeds and was equipped with accelerometers. The second vehicle was designed to acquire subsonic performance data and was heavily equipped with strain gauges, accelerometers, and pressure sensor orifices.

The first HiMAT flight took place on July 27, 1979, at Edwards Air Force Base in California. The aircraft flew for twenty-two minutes of stability and control tests before landing on the dry lakebed. The early HiMAT flights involved “gentle” maneuvers. The aircraft gradually increased the complexity of its maneuvers and underwent modifications in preparation for supersonic flight. The initial supersonic flight of the first HiMAT aircraft took place on May 11, 1982, flying at a maximum speed of Mach 1.2 at 12,192 meters altitude and remaining at supersonic speed for 7.5 minutes. The second supersonic flight took place on May 15, 1982, when the aircraft demonstrated a supersonic design point of Mach 1.4 and three g’s acceleration at 12,192 meters altitude. It flew for five minutes at supersonic speed and achieved a maximum acceleration of just under four g’s at Mach 1.4.

The second HiMAT aircraft made its first research data acquisition flight on May 26, 1982. It collected airspeed data and pressure, loads, and deflection data for aero-elastic tailoring assessment. It sustained a 5-percent negative static margin. On its second research data acquisition flight on June 2, 1982, the aircraft flight test maneuver autopilot acquired high-fidelity flight test data during wind-up turns and pushover, pullup maneuvers. The maximum acceleration attained was eight g’s. It achieved its maximum Mach number of 0.9 at 11,582 meters altitude.

The final flight occurred on January 11, 1983. The two vehicles flew a total of twenty-six times during the three-and-a-half-year program.[49]

The program investigated aircraft design concepts, such as relaxed static stability control, that could be incorporated on the fighter aircraft of

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[49] “HiMAT,” *NASA Facts On-Line,* FS-1994-11-025-DFRC, Dryden Flight Research Center, November 1994.

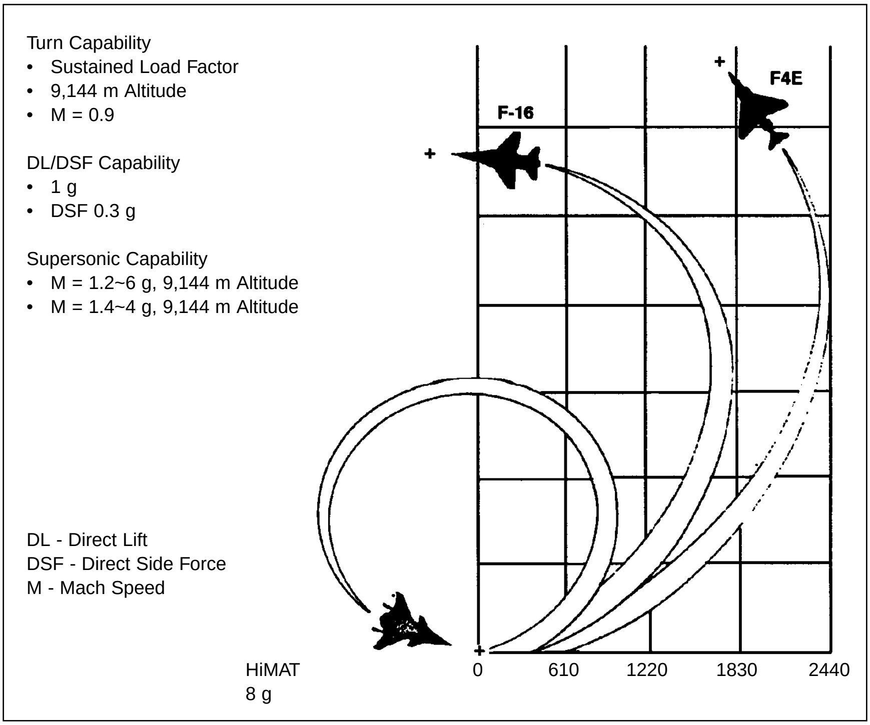

Figure 3–10. Increased Turning Capability of HiMAT Compared With Other Aircraft

the 1990s. Testing concentrated on high-g maneuvers at transonic and supersonic speeds. The vehicles provided data on the use of composites, aero-elastic tailoring, close-coupled canards (the smaller forward set of horizontal stabilizers), winglets (small vertical extensions of the wing tips), and the interaction of these then-new technologies on each other. Throughout the HiMAT test program, static stability—the tendency of an aircraft to return to its original attitude after being disturbed—was gradually reduced by relocating lead ballast from the nose to the tail of the aircraft to shift the center of gravity aft.[50] Turning performance of the canard-configured vehicle was improved by moving the center of gravity aft, although it reduced the aircraft's normal static stability.

The unique shape of HiMAT permitted high-gravity turns at transonic speeds—965 to 1,290 kilometers per hours. The rear-mounted swept wings and a forward controllable canard coupled to the flight control system provided the vehicles with twice the turning capability of military fighters (Figure 3–10).

About 30 percent of the materials used to build each HiMAT were composites. These materials—glass fibers and graphites—gave the structures additional strength for increased maneuverability and the high

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[50] William B. Scott, "HiMAT Maneuvering Goals Surpassed in Flight Test," *Aviation Week & Space Technology,* June 21, 1982, p. 38.

gravitational loads encountered during their flights. In HiMAT, graphite composites were used for the skin on the fuselage, wings, canards, engine inlet, vertical tails, and the wing and canard spars. Glass fiber composites were used for the leading edges of the outboard wings.

Both sets of airfoils were aero-elastically tailored to twist and bend in flight to the most favorable shape to achieve maximum performance for the particular flight conditions. The vehicle used the increased lift from the combination of the canards and wings to increase maneuverability at both subsonic and supersonic speeds.[51]

About one-half the size of a standard crewed fighter and powered by a small jet engine, the HiMAT vehicles were launched from NASA's B-52 carrier aircraft at an altitude of about 13,716 meters. A NASA research pilot flew them remotely from a ground station with the aid of a television camera mounted in the HiMAT cockpits. When the research portion of a HiMAT flight ended, the pilot landed the vehicle remotely on the dry lakebed adjacent to Dryden. The HiMATs were flown remotely because it was a safe way to test advanced technologies without subjecting a pilot to a high-risk environment. Remotely piloted research vehicles such as HiMAT could also be flown more economically than larger crewed vehicles.[52]

Each HiMAT had a DFBW control system instead of a conventional system. Lightweight wires replaced the heavier hydraulic lines and metal linkages that most aircraft used to transfer control commands to the movable surfaces on the wings and tail. Pilot commands were fed via telemetry to an on-board computer that sent electrical commands to the flight control surfaces. Fly-by-wire flight control systems were lighter in weight, were more versatile in terms of automatic features than conventional systems, and provided basic aircraft stability. This technology also saved weight and increased performance because the size of the normal stabilizing surfaces could be reduced.

The plane also incorporated an integrated propulsion system that used a digital computer to control the aircraft's entire propulsion system, instead of a conventional hydromechanical system. The system integrated control of the jet engine and nozzle, which vectored (tilted) during flight, permitting additional maneuverability without adverse interaction.

The vehicles were seven meters long and had a wingspan of close to about four and a half meters (Figure 3–11). They weighed 1,543 kilograms at launch and were powered by a General Electric J85 turbojet producing 22,240 newtons of thrust. The vehicles had a top speed of Mach 1.4 (Table 3–63).[53]

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[51] "HiMAT Research Plane to Make First Flight," *NASA News*, Release 79-90, June 28, 1979, p. 2.

[52] "HiMAT," FS-1994-11-025-DFRC.

[53] *Ibid.*

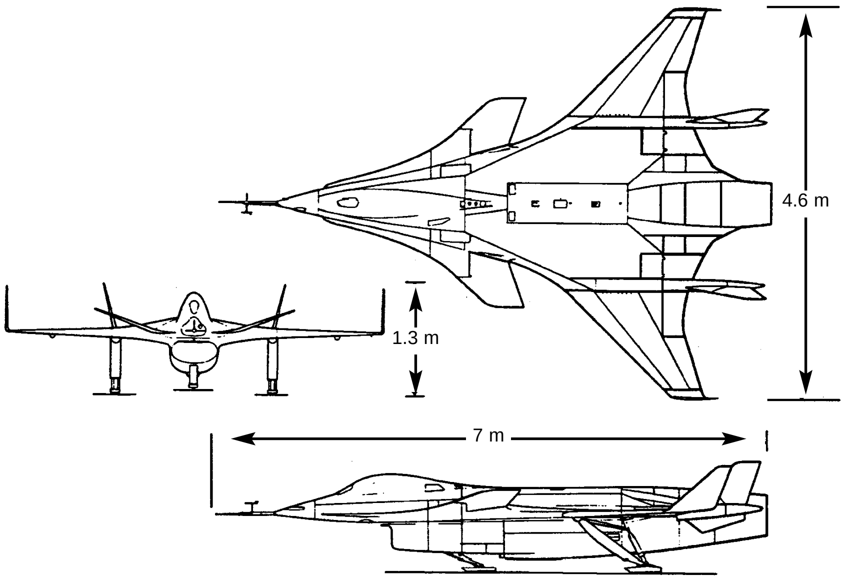

Figure 3–11. HiMAT Dimensions

One technology tested on the HiMAT vehicles that appeared later on other aircraft included the extensive use of composites that became common on military and commercial aircraft. Other technologies from the HiMAT tests appearing on other aircraft were the rear-mounted wing and forward canard configuration used on the X-29 research aircraft flown at Dryden and the winglets that were used on many private and commercial aircraft to lessen wingtip drag, increase stability, and enhance fuel savings.

X-29 Technologies

The X-29 research aircraft demonstrated the forward-swept wing configuration as well as the DFBW technology and flight control system addressed earlier. In December 1981, DARPA and the Air Force Flight Dynamics Laboratory selected Grumman Aircraft Corporation to build two X-29 aircraft, the first new X-series aircraft in more than a decade. The research aircraft were designed to explore the forward-swept wing concept and to validate studies that claimed the aircraft would provide better control and lift qualities in extreme maneuvers, reduce aerodynamic drag, and fly more efficiently at cruise speeds.

DARPA initially funded the X-29 program. NASA managed and conducted the X-29 flight research program at Dryden. The initial flight of the first X-29 took place on December 14, 1984, and the second first flew

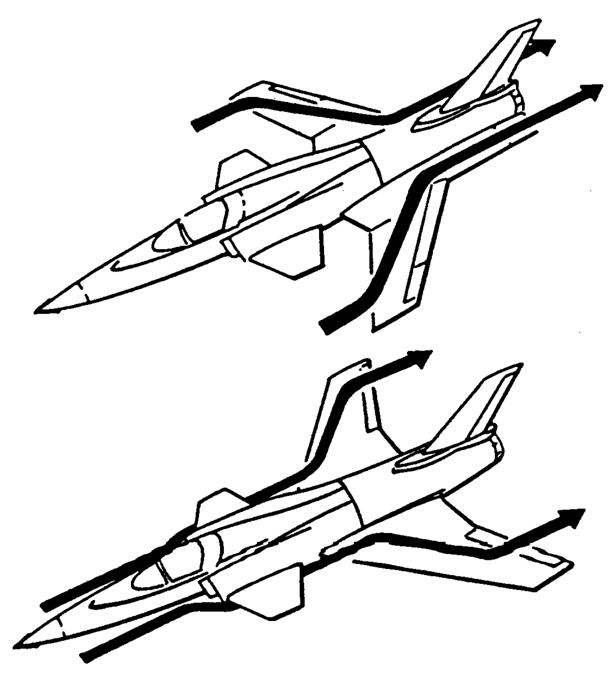

Figure 3–12. Forward-Swept Wing
(This design, shown in the top diagram, directs airflow inward behind the aircraft rather than outward.)

on May 23, 1989. Both flights were from Dryden. Table 3–64 gives the X-29's characteristics.

Forward-Swept Wing. The thirty-degree forward-swept wing configuration on the X-29 was mounted well back on the fuselage, while its canards—horizontal stabilizers to control pitch—were in front of the wings instead of on the tail. The complex geometries of the wings and canards combined to provide exceptional maneuverability, supersonic performance, and a light structure (Figure 3–12). The reverse airflow did not allow the wingtips and their ailerons to stall at higher angles of attack (the direction of the fuselage relative to the airflow).[54] Research results showed that the configuration of forward-swept wings, coupled with movable

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[54] Angle of attack (alpha) is an aeronautical term that describes the angle of an aircraft's body and wings relative to its actual flight path. During maneuvers, pilots often fly at extreme angles of attack—with the nose pitched up while the aircraft continues in its original direction. This can lead to conditions in which the airflow around the aircraft becomes separated from the airfoils. At high angles of attack, the forces produced by the aerodynamic surfaces, including lift provided by the wings, are reduced. This often results in insufficient lift to maintain altitude or control of the aircraft.

canards, gave pilots excellent control response at up to forty-five degrees angle of attack.[55]

Aero-elastic Tailoring. Germany first attempted to design an aircraft with a forward-swept wing during World War II, but the effort was unsuccessful because the technology and materials did not then exist to construct the wing rigidly enough to overcome bending and twisting forces without making the aircraft too heavy. The introduction of composite materials in the 1970s allowed for the design of airframes and structures that were stronger than those made of conventional materials, yet were lightweight and able to withstand tremendous aerodynamic forces. The use of composites made from carbon, Kevlar, glass, and other fibers embedded in a plastic matrix allowed a wing to be built that could resist the divergent forces encountered at high speeds. This technology, called aero-elastic tailoring, allowed the wing to bend, but it limited twist and eliminated structural divergence during flight.[56]

The X-29 wing had composite wing covers that used 752 crisscrossed tapes comprising 156 layers at their thickest point. The wing covers made up the top and bottom of the wing torsion box, the major structural element of the X-29 wing.

Thin Supercritical Wing. The composite wing also incorporated a thin supercritical wing section that was approximately half as thick as the supercritical wing flown on the F-8 (Figure 3–13). The thin supercritical wing design delayed and softened the onset of shock waves on the upper surface of a wing, deteriorating the smooth flow over the wing and causing a loss of lift and an increase of drag. The design was particularly effective at transonic speeds.

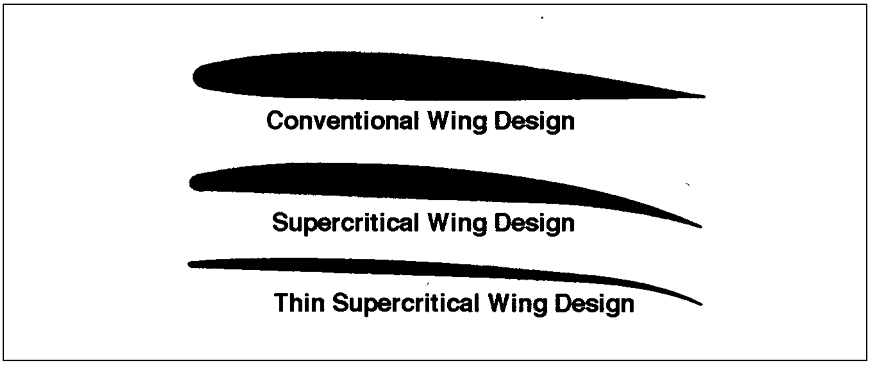

Figure 3–13. Relative Thickness of Conventional, Supercritical, and Thin Supercritical Wing Designs

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[55] "The X-29," *NASA Facts On-Line,* FS-98-04-008-DFRC, Dryden Flight Research Center, April 1998.

[56] Structural divergence is the deformation or the breaking off of the wing in flight.

Variable Camber. The X-29's flaperons (combination of flaps and ailerons) were composed of two segments. This feature allowed what was, in effect, a change of camber or wing curvature. The segmented flaperon could be "straightened" to adapt the wing to supersonic flight, creating the best combination of lift and drag for that speed range.

Close-Coupled Variable Incidence Canards. The canards, forward of and in line with the X-29's wings, provided the primary pitch control, shared the aerodynamic load with the wing, and added lift. The close-coupled canards channeled the airflow over the inboard wing area to resist wing root stall. Both right and left canards could move independently thirty degrees up or sixty degrees down.[57]

Strake Flaps. The strakes—the horizontal surfaces that extended along the rear fuselage from wing to the exhaust nozzle of the aircraft—were equipped with thirty-inch-long flaps that augmented the canards for pitch control.

Three-Surface Pitch Control. Simultaneous and continuous operation of the canards, flaperons, and strake flaps minimized trim drag and maximized the X-29's responsiveness at the onset of maneuvers. The canards provided primary pitch control; the flaperons provided roll control, high lift, and camber adjustments; and the strake flaps augmented the canards at low speeds, such as rotation for takeoff or recovery from a deep stall.

F-18 High Angle of Attack

NASA used an F-18 Hornet fighter aircraft in its High Angle of Attack Research Vehicle (HARV) program. This program, which began in 1987, attempted to expand what researchers called the "stall barrier"—the tendency of aircraft to stall and become uncontrollable at high angles of attack and slow speeds. This tendency greatly limited an aircraft's performance and maneuverability.[58]

NASA used the HARV to explore the use of thrust vectoring at high angles of attack. The research program produced technical data at high angles of attack to validate computer codes and wind tunnel research. The successful validation of these data could give engineers and aircraft designers a better understanding of aerodynamics, the effectiveness of flight controls, and airflow phenomena at high angles of attack. This could lead to design methods that provided better control and maneuverability in future high-performance aircraft and helped prevent dangerous spins and related crashes. The database would permit more efficient computer-aided design of aircraft and was expected to decrease wind tunnel and flight testing time. Costly postproduction design "fixes" could also be minimized.

The HARV program was a joint effort of NASA's Dryden Flight, Ames, Langley, and Lewis Research Centers. Ames examined aerody-

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[57] "The X-29," FS-98-04-008-DFRC.

[58] Wallace, *Flights of Discovery,* p. 103.

namic and vortex control concepts. Dryden had responsibility for flight vehicle demonstration and testing. Lewis investigated the thrust vector nozzle and propulsion technologies. Langley made extensive use of its wind tunnel and computer facilities to generate much of data that were being validated.

The first phase of high alpha flights began in mid-1987 using an unmodified aircraft. Investigators conducted visual studies of the airflow over various parts of the aircraft up to fifty-five degrees angle of attack. Special tracer smoke was released through small ports just forward of the leading-edge extensions near the nose and was photographed as it followed airflow patterns around the aircraft. Also photographed in the airflow were short pieces of yarn (tufts) taped on the aircraft, as well as an oil-based dye released onto the aircraft surfaces from 500 small orifices around the vehicle's nose.

The airflow patterns of smoke, dye, and tufts were recorded on film and videotape and compared with computer and wind tunnel predictions. Additional data obtained included air pressures recorded by sensors located in a 360-degree pattern around the nose and at other locations on the aircraft. The first phase lasted two and a half years and consisted of 101 research flights.

In 1987, NASA selected McDonnell Douglas Corporation to equip the research aircraft with a thrust vector control system about the pitch and yaw axes.[59] The system had an easily programmable research flight control system that allowed research into flight control concepts using various blends of aerodynamics and thrust vector control at subsonic and high alpha flight conditions. These thrust-vectoring paddles helped stabilize the aircraft at extremely high angles of attack. The modified Hornet was used for subsequent phases of the program, which was still under way in 1996.

X-31

The development of the X-31, a highly maneuverable fighter-type plane, began in the late 1980s. Funded by DOD and West Germany, the program used NASA's Dryden Flight Research Center for some of its testing.

Hypersonics: The National Aerospace Plane Program

NASA's hypersonic research in the late 1970s and early 1980s was conducted primarily at Langley Research Center under a minimal budget. Researchers at Langley developed subscale versions of the scramjet (supersonic combustion ramjet) and conducted numerous tests in supersonic

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[59] "McDonnell Douglas Selected for Contract Negotiations," *NASA News,* May 1, 1987.

combustion.[60] The advent of high-speed digital computers and advanced metal-matrix composites increased the rate of progress in this field.

Developments in computational fluid dynamics, principally at NASA's Ames Research Center, paralleled the development in scramjet technology. The advent of supercomputing capabilities allowed for more detailed analyses and simulation of the aerodynamics and thermodynamics associated with sustained hypersonic cruise and exiting and entering Earth's atmosphere at various trajectories. Advanced computational fluid dynamics codes also assisted in understanding the supersonic airflow through scramjet configurations.[61]

In 1982, DARPA initiated an effort at Langley called Copper Canyon, which would be Phase I of the National Aerospace Plane (NASP) program. This phase incorporated recent research in the areas of hypersonic propulsion, advanced materials and structures, and computational fluid dynamics. Technically, the largest challenge was in the field of propulsion technology. The proposed vehicle needed a combination engine that covered a wide range of Mach speeds. In the lower speed range up to Mach 5, turbojet or subsonic ramjet engines were required, but above those speeds, the vehicle required either the scramjet or a combination scramjet and scramrocket. In contrast to ramjets, scramjets do not slow the air to subsonic speed so that the air can be used to burn liquid hydrogen, but rather, they burn the hydrogen in supersonic streams at lower temperatures. This would increase engine efficiency, proponents of the program stated, and could lead to a significant reduction in launch costs to low-Earth orbit.

The program's goal was to develop and demonstrate the technologies needed to fly an aircraft into orbit by using airbreathing propulsion instead of rockets. The eventual intent was to build and fly an actual experimental transatmospheric vehicle that would take off horizontally from a conventional runway, accelerate from 0 to Mach 25, and be capable of leaving Earth's atmosphere, then enter into low-Earth orbit, return to the atmosphere, and land, again horizontally. Its airbreathing engines (scramjet technology) would use oxygen from the environment to burn its fuel rather than carry its own oxygen supply, as rockets do.[62]

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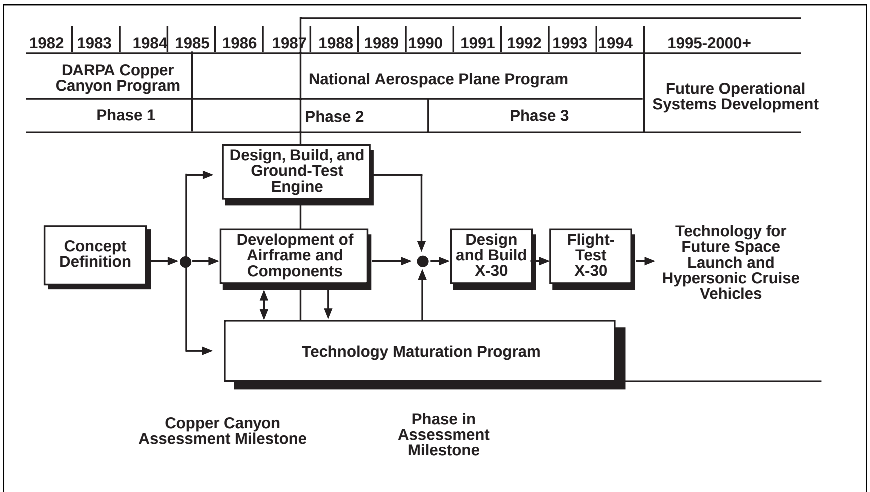
[60] "NASA 'Hyper-X' Program Established—Flights Will Demonstrate Scramjet Technologies," *NASA Facts On-Line,* FS-1998-07-27-LaRC, Langley Research Center, July 1998. A scramjet is a ramjet engine in which the airflow through the whole engine remains supersonic. A ramjet is an air-breathing engine similar to a turbojet but without mechanical compressor or turbine. Compression is accomplished entirely by ram and is thus sensitive to vehicle forward speed and is nonexistent at rest.

[61] John D. Moteff, "The National Aero-Space Plane Program: A Brief History," *CRS Report for Congress,* 88-146 SPR (Washington, DC: Congressional Research Service, The Library of Congress, February 17, 1988), p. 3.

[62] John D. Moteff, "National Aero-Space Plane," *CRS Report for Congress* (Washington, DC: Congressional Research Service, The Library of Congress, updated January 2, 1991 (archived)), p. 2.



Source: U.S. General Accounting Office

Figure 3–14. National Aerospace Plane Program Schedule and Milestones

It was envisioned that horizontal takeoff and landing would provide flexible basing and reduce reliance on the launch and landing facilities at Kennedy Space Center and Edwards Air Force Base, respectively. They might also reduce operational costs and shorten turnaround time. The aircraft would demonstrate the capability for flying single-stage-to-orbit without carrying large disposable fuel tanks or having stages that separated as the vehicle gained altitude. It would also be unique in that the engines would be integrated with the airframe rather than separate units that were bolted to the wings.[63] Other goals were a powered landing capability and maximum aircraft-like maneuverability.[64] The plane would have both military and civilian applications.

Program Development. The program was to consist of three phases (Figure 3–14). Phase I, Copper Canyon, began at Langley Research Center in 1982. This phase, concept definition, focused on scramjet technology and involved several government agencies and private firms and universities in tests and design studies to determine the feasibility of transatmospheric vehicles. During this phase, researchers investigated a hydrogen-based power aircraft that would be capable of horizontal takeoff and landing and operating at speeds between Mach 12 and 25 at altitudes between 30,480 and 106,680 meters.

In 1985, DARPA and NASA completed the definition of an air-breathing aerospace plane, and NASA stated its conviction that a hypersonic transatmospheric vehicle was technically feasible. NASA's

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[63] Larry Schweikart, "Hypersonic Hopes: Planning for NASP, 1986–1991," *Air Power History,* Spring 1994, p. 36.

[64] Moteff, "National Aero-Space Plane," p. 3.

Dr. Raymond S. Colladay, the associate administrator of OAST, cited "significant activities" at NASA in support of the hypersonic vehicle. These included:

- A cooperative program with DARPA to develop a database for the required combined cycle airbreathing engine
- Continuing scramjet research
- Identification of airframe/propulsion integration as the key to achieving acceptable performance for a hypersonic cruise airplane
- Space Shuttle experiments to produce data important to hypersonics and transatmospherics
- Planned major facility modifications to permit the full-scale verification of scramjet combustion systems at the high-temperature tunnel at Langley Research Center, testing of combined cycle engine concepts at the propulsion system lab at Lewis Research Center, and flow-field studies at the hypersonic tunnel at Ames Research Center
- A joint program with the Office of Naval Research and the Air Force Office of Scientific Research to initiate a new research program at universities in FY 1986 in hypersonic viscous flows[65]

DOD also expressed optimism. U.S. Air Force Maj. General Donald J. Kutyna stated that DOD had decided to proceed with a $500 million program to design a hypersonic plane that could fly around the globe in less than two hours and in the highest reaches of the atmosphere. He envisioned this vehicle capable of providing a low-cost method for launching satellites and other equipment critical to the Strategic Defense Initiative.

Funding responsibility for the program would be divided between NASA and DOD, with NASA assuming 20 percent of the funding burden and DOD assuming the other 80 percent.[66] During the early research and development activities, NASA would carry a larger portion of the funding burden.

As it advanced in late 1985, the program was a large team effort. In addition to NASA and DOD (represented by DARPA), the U.S. Air Force, U.S. Navy, and Strategic Defense Initiative Organization also participated. DOD was responsible for overall management of the joint program. NASA had lead responsibility for overall technology direction, application studies, and the design, fabrication, and flight testing of experimental flight vehicles. Within DOD, the Air Force was assigned overall responsibility for the program. In the 1986 memorandum of understanding, DARPA was given the lead for early technology devel-

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[65] "NASA Moving Out on Hypersonic Vehicle Research," *Defense Daily,* August 1, 1985, p. 172.

[66] Brendan M. Greeley, Jr., "U.S. Moves Toward Aerospace Plane Program," A*viation Week & Space Technology,* December 16, 1985, p. 16.

opment (Phase II), and the Air Force had the lead for Phase III technology development.[67]

Phase II began in 1986, following the formal establishment of the NASP program in 1985. This technology development phase consisted of the accelerated development of key technologies, airframe design, propulsion module development, and ground tests of the propulsion system up to Mach 8—the then-current practical limit of wind tunnels for engine tests.[68] NASA and the Air Force awarded numerous contracts in the spring of 1986. The contracts in the general areas of propulsion and airframe called for research and development in propulsion, aerodynamics, computational fluid mechanics, advanced structures, and high-temperature materials that would lead to the design of a NASP flight research vehicle called the X-30. Potential total contract value was more than $450 million.[69] In November 1986, the NASA administrator approved Duncan E. McIver's appointment as director of the NASP Office.[70]

President Ronald Reagan strongly advocated the program. When he mentioned a hypothetical commercial vehicle in his February 1986 State of the Union address, in his call for research into "a new Orient Express," he was really referring to the NASP program.[71]

Design Concepts. Four design concepts were under consideration (Figure 3–15). The blended body was elliptically shaped and used an engine integrated in the lower surface of the airframe. The design had structural weight and thermal protection advantages, but the baseline concept that was selected offered better low-speed control and efficiency.

The cone body featured an aerodynamically shaped cylindrical airframe ringed by engines. The advantages of that concept included large thrust capabilities and large fuel capacity. Compared with the baseline, the cone body was less aerodynamically efficient and had less vehicle stability and control.

The combination body had a turtle-shaped body with rounded scramjets located on the lower surface of the airframe. Although this design was as efficient as the wing body, the combination body had a higher structural weight and required greater thermal protection.[72]

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[67] "Memorandum of Understanding Between the Department of Defense and the National Aeronautics and Space Administration for the Conduct of the National Aero-Space Plane Program," June 1986, National Historical Reference Collection, NASA History Office, NASA Headquarters, Washington, DC.

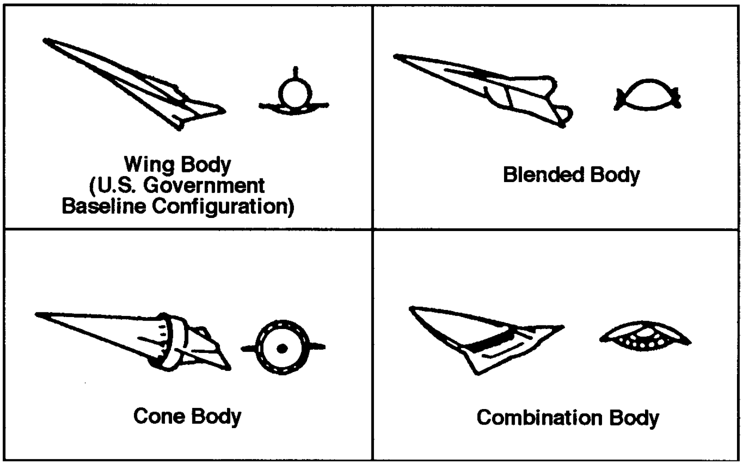
[68] "The National Aerospace Plane Program," *Aerospace,* Spring 1986, p. 2.

[69] "National Aerospace Plane Program Awards Contracts," *NASA News*, April 7, 1986.

[70] "Duncan McIver Appointed Director, National Aero-Space Plane Office," *Headquarters Bulletin*, NASA, January 5, 1987, p. 6.

[71] Moteff, "The National Aero-Space Plane Program," p. 1.

[72] Stanley W. Kandebo, "Researchers Pursue X-30 Spaceplane Technologies for 1990 Evaluation," *Aviation Week & Space Technology,* August 8, 1988, p. 50.



Source: "Researchers Pursue X-30 Spaceplane Technologies for 1990 Evaluation," *Aviation Week & Space Technology,* August 8, 1988, p. 49.

Figure 3–15. Four Generic X-30 Designs With Fully Integrated Engines and Airframes

All of the designs featured an integrated engine and airframe. The vehicle would be about the size of a Boeing 727 transport and use three to five scramjet engines and a single rocket that produced approximately 200,000 to 300,000 newtons of thrust. Its weight at takeoff would be approximately 113,000 to 136,000 kilograms. The X-30 test vehicle would have little payload capacity beyond the ability to carry a crew and test instrumentation and would require about 45,360 kilograms of slush hydrogen (partly liquid and partly frozen) per mission.

The design baseline for the X-30 (as of August 1988) was the wing body configuration (Figure 3–16). The wing body had a rounded fuselage and positioned the engine underneath the airframe. Although the design was aerodynamically efficient, permitted a large fuel tank, and offered good low-speed control, problems existed in integrating the airframe afterbody with the engine exhaust nozzles.

During this period, the participants expressed confidence that the program would progress as planned. Colladay testified before Congress that the NASP program was making good technical progress and said that initial applications of the vehicle would most likely be for the government, either as a launch system or as a strategic military vehicle. Presidential Science Advisor Dr. William R. Graham told the Senate subcommittee on space that only an insurmountable technical barrier could prevent the United States from proceeding with the plane, and no such barrier was presently foreseen.[73] Air Force Colonel Len Vernamonti, chief of the NASP program, agreed that researchers had encountered no obstacles in their theoretical work on the plane.

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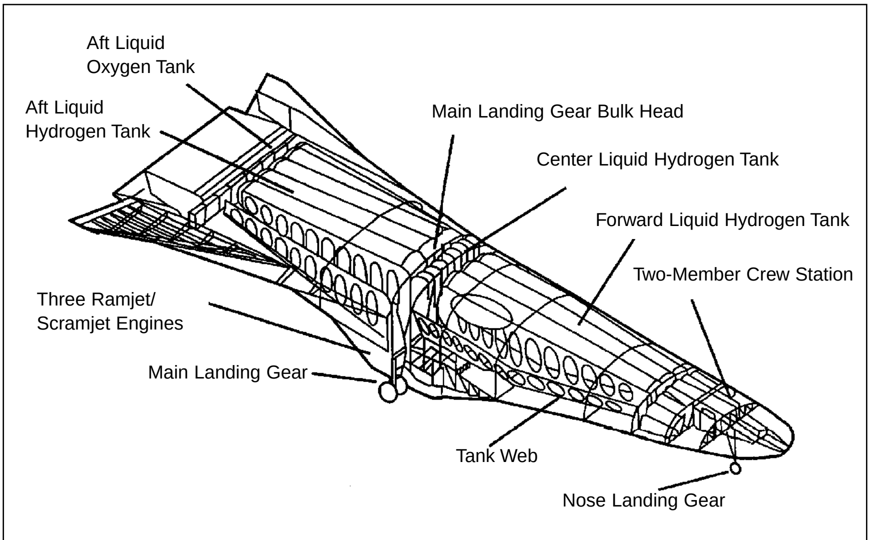
[73] "Graham Sees No Barrier to X-30 Space Plane," *Defense Daily,* March 2, 1987, p. 1.



Source: NASA Photo HqL-34B

Figure 3–16. Proposed National Aerospace Plane

However, others within DOD expressed concerns. DOD Director of Operational Test and Evaluation John Krings told the Senate subcommittee on industry and technology that existing facilities were "barely adequate to support the experimentation and feasibility demonstration phases for [new] technology programs, let alone the development and operational testing and evaluation that will be required as they matured."[74] A Defense Science Board task force recommended that DOD slow the schedule for producing a NASP experimental vehicle by at least one year because the advanced technology components, such as materials, relied on by engine and airframe designers were not yet available.[75]

When the program outgrew DARPA's traditional R&D functions in 1988, the program moved to the Air Force in preparation for the development of a flight test vehicle. DOD signed the new memorandum of understanding in August 1988, and NASA signed it in September of that year.[76] If times had been different, NASA might have offered to assume program responsibility. But in 1988, NASA was involved with

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[74] "New Space Systems Test Facilities to Cost $7 Billion," *Aviation Week & Space Technology,* April 27, 1987, p. 85.

[75] "DSB Expected to Propose Slowdown in NASP Program, More Technology Research," *Inside the Pentagon,* September 18, 1987, p. 1.

[76] "Memorandum of Understanding Between the Department of Defense and the National Aeronautics and Space Administration for the Conduct of the National Aero-Space Plane Program," September 1986, NASA Historical Reference Collection.

reinvigorating the Space Shuttle program, planning a new heavy-lift rocket, and working on the Space Station.[77]

The program became more controversial as it progressed, and funding problems developed. The Senate Armed Services Committee reduced the Air Force's FY 1988 request for R&D funds for the NASP program from $236 million to $200 to boost NASA's share of the program costs, which increased 1 percent to 19.2 percent in the FY 1988 budget.[78] The program was threatened with up to a 33-percent budget cut in FY 1988 from congressional actions, which could lead to at least a one-year slip. This would require that private-sector contractors continue to fund the program heavily with their own money, which, in some areas, amounted to four times the government's contribution.[79]

Funding constraints pushed the X-30 about a year behind schedule as of the spring of 1988, with the first flight delayed to 1994 or 1995. Also, although NASA stated that both the NASP program and the Space Station deserved a sufficient level of funding, it found the two programs competing for limited funds. Beginning in 1989, funding levels generally dropped. President George Bush's Secretary of Defense, Richard Cheney, proposed eliminating DOD funding of the NASP program and recommended transferring the program entirely to NASA. The President's budget showed that DOD's share of the program would be transferred to NASA along with program management. Congress restored the program's joint NASA-DOD funding and recommended that DOD retain program management. Congress also recommended that Phase II be extended and that a decision whether to proceed with building the X-30 be postponed until March 1993.

Phase III was to have begun in 1990. This phase called for the selection of one engine contractor and one airframe contractor to design and build two X-30s to explore propulsion performance above Mach 8. Structures and materials needed to fabricate such a vehicle would be developed and tested. It was originally intended that a decision to proceed with this phase would be made in 1988. However, as the events just described show, at the end of 1988, technology development had not yet progressed to a point where a decision could be made.

DOD pulled out of the program in 1993. It survived until FY 1994, when Congress reduced NASA's funding to $80 million.[80] It eliminated all remaining funding in FY 1995.

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[77] Schweikart, "Hypersonic Hopes," p. 43.

[78] "Defense Digest," *Defense Daily,* May 15, 1987, p. 91.

[79] "Washington Roundup," *Aviation Week & Space Technology,* November 2, 1987, p. 21.

[80] Stanley W. Kandebo, "NASP Cancelled, Program Redirected," *Aviation Week & Space Technology,* June 14, 1993, p. 33.

Safety and Flight Management

Operational and safety problems have been traditional topics for NASA aeronautical research. Flights in bad weather, landings on wet runways, and airport approaches during periods of high-density traffic flow have been studied and improved by NASA programs, often working cooperatively with the FAA. NASA programs were conducted in technological areas, such as materials and structures and guidance and control, and in human factors areas, such as how pilots interact with various cockpit displays or react to unexpected weather conditions.

Transport Systems Research Vehicle

Although not a program, NASA's Transport Systems Research Vehicle (TSRV) deserves special mention. This Boeing 737-100 was the prototype 737, acquired by Langley Research Center in 1974 to conduct research into advanced transport aircraft technologies. In the twenty years that followed, the airplane participated in more than twenty different research projects, particularly focused on improving the efficiency, capacity, and safety of the air transportation system. It played a significant role in developing and gaining acceptance for numerous transport technologies, including "glass cockpits," airborne wind shear detection systems, a data link for air traffic control communications, the microwave landing system, and the satellite-based global positioning system (GPS).

The TSRV's unique research equipment included a complete second cockpit in the cabin (Figure 3–17). The plane had three major subsystems. One subsystem operated the actual flight controls of the airplane. A second subsystem provided computerized navigation functions, which controlled the airplane's flight path. The third subsystem operated the electronic flight displays in the aft cockpit. The on-board computer equipment was regularly upgraded to keep pace with rapid developments in computer technology.

The aircraft served as a focus for joint NASA-industry research efforts as well as joint efforts with other government agencies.[81] The following sections address programs that made use of this unique vehicle from 1979 to 1988. Table 3–65 gives the aircraft's specifications.

Terminal-Configured Vehicle/Advanced Transport Operating System Program

The Terminal-Configured Vehicle (TCV) program, a joint NASA-FAA effort, began in 1973. In June 1982, the name of the TCV program was changed to the Advanced Transport Operating System (ATOPS)

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[81] Lane E. Wallace, *Airborne Trailblazer: Two Decades With NASA Langley's 737 Flying Laboratory* (Washington, DC: NASA SP-4216, 1994), p. vii.

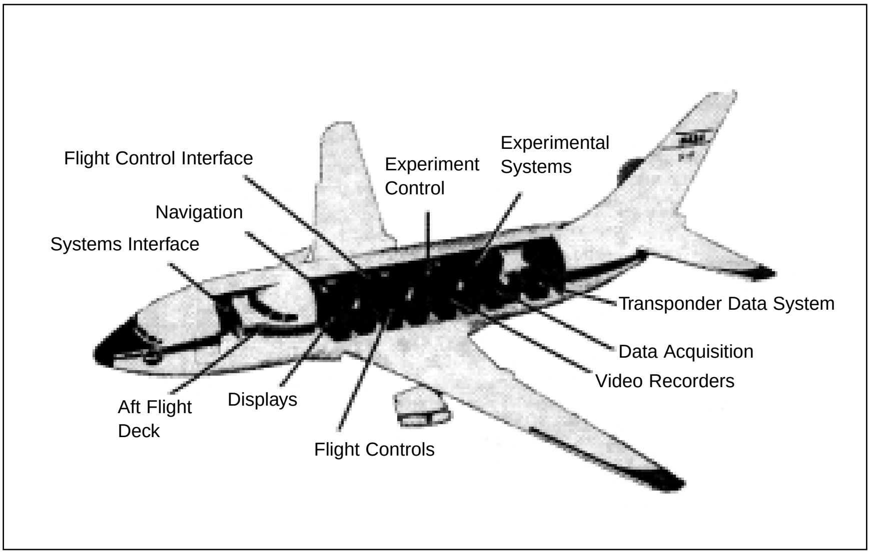

Figure 3–17. NASA Transport Systems Research Vehicle (TSRV)
(The plane was flown from the research cockpit, located in the forward fuselage. Safety pilots in the conventional cockpit served as backup to the research pilots and could fly the airplane if required. Seating behind the research cockpit was for flight test engineers who monitored and interpreted the video display system. The TSRV could be reconfigured for various research purposes.)

program, to reflect its renewed emphasis on commercial air transportation system issues, rather than on individual airplane technologies.[82]

One area of the program addressed the techniques needed to achieve time-controlled descent to an airport. The program used the TSRV to investigate advanced technology for conventional takeoff and landing aircraft. The program examined approach paths for noise abatement and improved airport acceptance rates, cockpit displays of traffic information, and profile and time-based navigation (which would use a computer to calculate an optimum fuel-efficient flight plan to sort out and sequence arriving aircraft in a time-based traffic control system that matched airport demand to its capacity and allowed closer spacing of aircraft).

Research could place aircraft at a point in space, for example, at the start of the descent to the airport within a few seconds. If there were unfavorable winds, that time might increase by as much as ten seconds; however, that compared with perhaps two minutes' accuracy with conventional methods of air traffic control. The descent itself, handled by the "smart" avionics in the TSRV, would be done along a flight path that used minimum fuel, so there would be potential fuel savings by using the system. Other potential payoffs included routine operations in bad weather, pilot participation in the traffic control system loop by using a cockpit

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[82] *Ibid.*, p. 21.

display of traffic, reduced lateral separation and spacing, and reduced runway occupancy time. All of these factors tended to increase the capacity of an airport in all kinds of weather.

Several research projects in the ATOPS program were geared toward improving the internal systems and operation of transport aircraft. One was the Digital Autonomous Terminal Access Communication (DATAC) project. Boeing had developed the technology for a single, global data bus that would carry the information between the different components of an airplane's systems. NASA expressed an interest in the system for its TSRV, and in 1983, the initiative became the joint DATAC project. Boeing designed and built the data bus and the terminals that provided the interface between the data bus and the computers or components using the system. NASA engineers designed the interface boxes and software that would convert the data from the format needed for transmission on the data bus to a format the TSRV's computers and experimental systems could understand. By 1984, the DATAC system was installed and operating successfully on the TSRV. In 1985, Boeing became interested in using the system on its new airliners and incorporated it in its new transports, the 777s.

The Total Energy Control System (TECS) project attempted to make an autopilot/autothrottle system perform more like an actual pilot by designing a more efficient, integrated system that would make better use of an airplane's stored energy. From 1979 to 1981, NASA contracted with engineers at the Boeing Commercial Airplane Company to develop the control laws the system would require. Engineers at Boeing designed a system that would use the throttle and the elevator to control the energy state of the plane and the distribution of that energy from flight path to normal flight speed.

TECS was first tested successfully in the Boeing 737 simulator at Langley Research Center. NASA engineers then programmed it into TSRV flight computers and conducted twenty hours of flight testing in 1985. The system worked as expected, and the pilots liked the system. Nevertheless, because implementing TECS would require complete redesign of the automatic control system on commercial airliners, it was not incorporated into any of Boeing's commercial planes. It was, however, used on the uncrewed Condor aircraft that was remotely piloted.[83]

Cockpit Technology

As pilots moved from landing aircraft on a straight path that often approached ten miles or more to relying on steep, curved approach paths with final distances as short as one mile, they required a more accurate picture of the airplane's position at all times. They also had to control the airplane's progress precisely and monitor accurately any automatic systems so they could take over if necessary. This degree of monitoring and

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[83] *Ibid.*, pp. 81–82.

management was virtually impossible with the conventional displays used during the mid-1970s. A new technology used cathode ray tube displays, developed as part of the TCV program, to process the raw aircraft system and flight data into an integrated, easily understood picture of the aircraft.[84]

The TCV experiments with electronic flight displays examined the effectiveness of the displays and how they could be used in a transport cockpit. In addition to validating the benefits of the basic equipment, researchers investigated and evaluated several display concepts to examine whether they would improve pilot awareness and the ability to compensate and correct for flight path errors.

Much of the development work in the early 1980s was conducted in the TSRV simulator at Langley Research Center, which duplicated the aft flight deck on the TSRV. The "all-glass" concept presented information to crew members on eight electronic displays that matched the TSRV aircraft. The crew members used the simulator to investigate new concepts in flight station design that would provide for safer and more efficient system operations by reducing clutter and improving the orderly flow of information controlled by the flight crew. Using the simulator allowed for the evaluation of various displays and also permitted research on improving situational awareness, air traffic control communication, flight management options, traffic awareness, and weather displays.[85] Promising display concepts were then incorporated into the TSRV's aft flight deck for operational testing.

The initial displays were monochrome cathode ray tubes. These were replaced by eight twenty-centimeter-squared electronic color displays representing the technology to become available in commercial transports of the future. The state-of-the-art color displays were driven by new on-board computers and specially developed computer software. These new technologies allowed information to be displayed more clearly than would be the case on existing electromechanical and first-generation electronic displays on current aircraft. The displays gave the pilots integrated, intuitively understandable information that provided a more accurate picture of the airplane's exact situation at all times. Pilots were expected to use this information to monitor and control airplane progress much more effectively and precisely than by using conventional displays.

Later in the 1980s, NASA began investigating the technology necessary to design "error-tolerant" cockpits that included a model of pilot behavior. The system used this model to monitor pilots' activities, such as track pilot actions, infer pilot intent, detect unexpected actions, and alert the crew to potential errors. A related investigation at Ames Research

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[84] *Ibid.*, pp. 26–27.

[85] Randall D. Grove, ed., *Real-Time Simulation User's Guide; "The Red Book"* (Hampton, VA: Analysis and Simulation Branch, NASA Langley Research Center, January 1993), ch. 3, sec. 3.3.3 [no page numbers].

Center, using the Man-Vehicle Systems Research Facility, examined the human side of the people-machine relationship, including human error, fatigue, stress, and the effects of increasingly automated technologies on flight crew performance.

The advent of computerization and automation in the cockpits of commercial airliners resulted in a variety of benefits. Aircraft could travel on more fuel-efficient flight paths, use more reliable equipment that had greater flexibility for upgrades, and operate with only two pilots, no matter how large the aircraft. However, the new technology led to some unexpected problems. Human factors became an integral part of design analysis, and researchers looked closely at optimum levels of pilot workload and ways to keep pilots involved in the computerized systems. Initially, there was some concern that the pilots' workload would be decreased to the point where their skills would also lessen. However, researchers found that their workload actually increased to too high a level. One of the components of the system, the control and display unit, required so much attention that the pilots would neglect to look out the windows for visual information. Training had to be adjusted so that pilots learned when it was appropriate to use the control and display units and when to hand-fly the aircraft.[86]

Wind Shear

Wind shear refers to any rapidly changing wind current. It is characterized by almost instantaneous reversals of wind speed and direction. Microbursts are local, short-lived severe downdrafts that radiate outward as they rush toward the ground. They can produce extremely strong wind shear. As a downdraft spreads both downward and outward from a cloud, it creates an increasing headwind over the wings of an oncoming aircraft. This headwind causes a sudden leap in airspeed, and the plane lifts.

If the pilot is unaware that wind shear caused the increase in speed, the reaction will be to reduce engine power. However, as the plane passes through the shear, the wind quickly becomes a downdraft and then a tailwind. The speed of air over the wings decreases, and the extra lift and speed rapidly fall to below original levels. Because the plane is then flying on reduced power, it is vulnerable to sudden loss of airspeed and altitude. The pilot may be able to escape the microburst by increasing power to the engines. But if the shear is strong enough, the aircraft may crash.[87] Figure 3–18 illustrates the effects of wind shear on an aircraft.

Wind shear poses the greatest danger to aircraft during takeoff and landing, when the plane is close to the ground and has little extra speed or time or room to maneuver. During landing, the pilot has already reduced engine power and may not have time to increase speed enough to

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[86] Wallace, *Airborne Trailblazer,* pp. 36–37.

[87] "Making the Skies Safe From Windshear," *NASA Facts,* NF176 (Hampton, VA: Langley Research Center, June 1992).

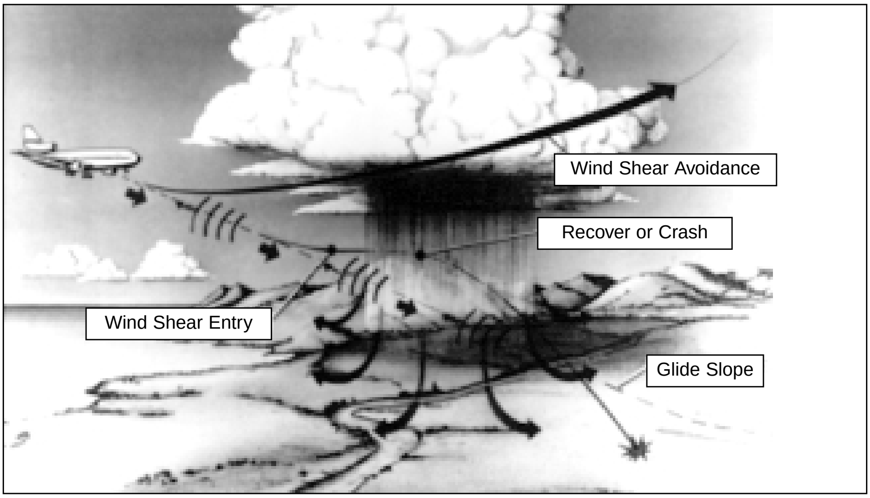

Figure 3–18. Artist's Depiction of the Effect of Wind Shear on an Aircraft (Wind shear is dangerous to aircraft primarily during takeoff and landing.) (NASA Photo 92-HC-423)

escape the downdraft. During takeoff, an aircraft is near stall speed and thus is very vulnerable to wind shear.

Microburst wind shear often occurs during thunderstorms. But it can also arise in the absence of rain near the ground. Some of the sensor systems that Langley Research Center tested worked better in rain, while others performed more successfully during dry conditions.

Beginning in 1976, more than 100 U.S. airports installed the FAA-developed ground-based low-level wind shear alert system, which consisted of an array of wind velocity measuring instruments located at various spots around an airport. The system compared the wind direction and velocity readings from the different sensors and, if significant variations between sensors were detected, transmitted an alert to the air traffic controllers, who then notified pilots in the area. The system, however, could not measure winds above the ground sensors, record vertical wind forces, or predict the approach of wind shears. Although this system was an improvement over existing detection methods, an on-board warning system with the capability to warn pilots of wind shear in time for them to avoid it was still needed.[88]

In 1986, Langley and the FAA signed a memorandum of agreement authorizing the start of a program to develop technology for detecting and avoiding hazardous wind shear. The five-year $24 million research project, the Airborne Windshear Detection and Avoidance Program, came in response to congressional directives and National Transportation Safety Board recommendations that followed three fatal accidents and numerous other nonfatal accidents linked to wind shear. In 1988 the FAA directed

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[88] Wallace, *Airborne Trailblazer,* p. 58.

that all commercial aircraft must have on-board wind shear detection systems installed by the end of 1993.

The program had three major goals. The first goal was to find a way to characterize the wind shear threat in a way that related to the hazard level it presented for aircraft. The second was to develop airborne remote-sensor technology to provide accurate, forward-looking wind shear detection. The third was to design flight management concepts and systems to transfer that information to pilots so they could respond effectively to a wind shear threat.[89]

The program covered five major technology areas: technology assessment, present position sensor integration, hazard characterization, pilot factors in wind shear, and effects of heavy rain. The effort produced a database on microbursts and detection systems with data gathered from analyses, simulations, laboratory tests, and flight tests that would help the FAA certify predictive wind shear detection systems for installation on all commercial aircraft.

Roland Bowles, manager of the Langley wind shear research program, devised the "F-Factor" as an index to describe the hazard level of the wind shear. The index, which would be displayed in the cockpit, measured the loss in rate-of-climb capability that would result from flying into a wind shear. The higher the F-Factor, the greater the hazard. Information from past wind shear accidents indicated that the wind shear became a serious hazard when the F-Factor reached 0.1. Thus, the cockpit warning would be preset to alert the crew whenever that point was reached.[90] The F-Factor of a wind shear also would indicate how much extra power an airplane needed to fly through it without losing airspeed or altitude.[91]

Experts agree that avoidance is the best approach to take when encountering a wind shear situation. NASA, the FAA, and industry partners developed three systems that would warn pilots of wind shear so that they could avoid it: microwave radar, light detecting and ranging (LIDAR), and infrared (Figure 3–19). These three systems had been discussed in a 1983 report released by the National Academy of Sciences that recommended continued research into airborne wind shear detection systems. The systems gave pilots from ten to forty seconds' advance warning of the approaching wind shear. (Pilots need ten to forty seconds of warning to avoid wind shear; fewer than ten seconds is not enough time to react, while changes in atmospheric conditions can occur if more than forty seconds elapse.) Flight tests of the three systems began in the summer of 1991 in Orlando, Florida, and in Denver, Colorado, once more using the TSRV.

In addition to the sometimes fatal impact that wind shear has had on airplanes, some investigators believe that severe wind shear affected the Space Shuttle *Challenger* in its 1986 accident and may have magnified

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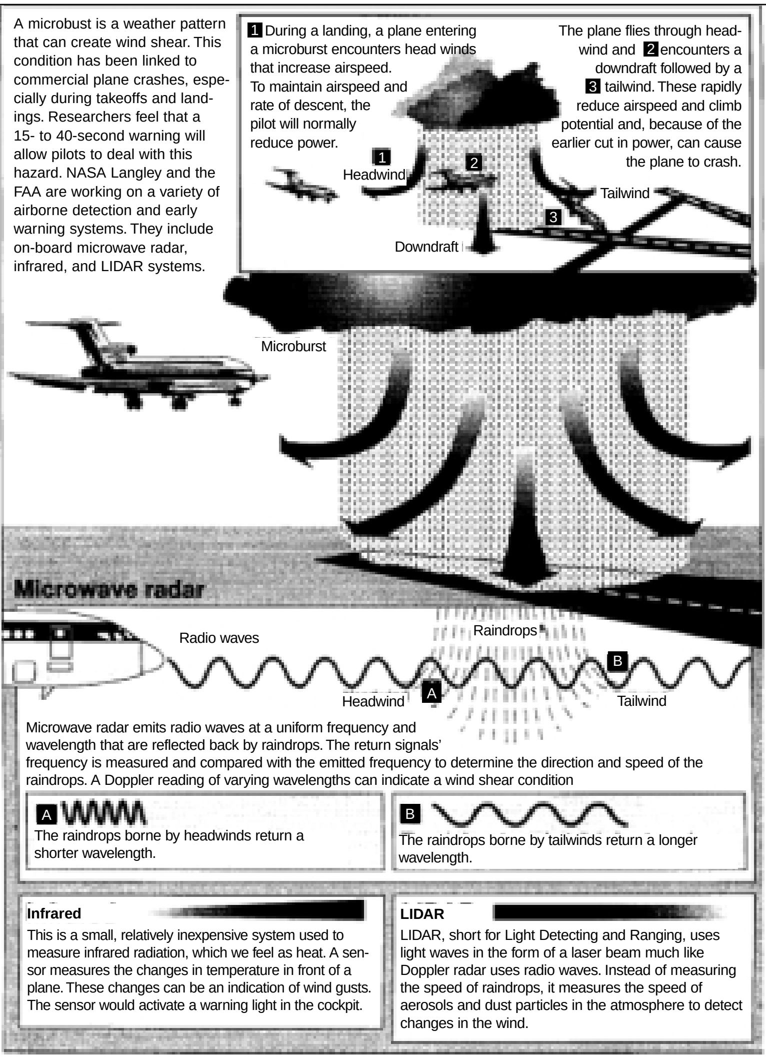
[89] *Ibid.,* p. 61.

[90] "The Hazard Index: Langley's 'F-Factor,'" *NASA Facts,* NF177 (Hampton, VA: Langley Research Center, June 1992).

[91] Wallace, *Airborne Trailblazer,* p. 63.



A microbust is a weather pattern that can create wind shear. This condition has been linked to commercial plane crashes, especially during takeoffs and landings. Researchers feel that a 15- to 40-second warning will allow pilots to deal with this hazard. NASA Langley and the FAA are working on a variety of airborne detection and early warning systems. They include on-board microwave radar, infrared, and LIDAR systems.

1 During a landing, a plane entering a microburst encounters head winds that increase airspeed. To maintain airspeed and rate of descent, the pilot will normally reduce power.

The plane flies through headwind and 2 encounters a downdraft followed by a 3 tailwind. These rapidly reduce airspeed and climb potential and, because of the earlier cut in power, can cause the plane to crash.

Microwave radar emits radio waves at a uniform frequency and wavelength that are reflected back by raindrops. The return signals' frequency is measured and compared with the emitted frequency to determine the direction and speed of the raindrops. A Doppler reading of varying wavelengths can indicate a wind shear condition

A The raindrops borne by headwinds return a shorter wavelength.

B The raindrops borne by tailwinds return a longer wavelength.

Infrared

This is a small, relatively inexpensive system used to measure infrared radiation, which we feel as heat. A sensor measures the changes in temperature in front of a plane. These changes can be an indication of wind gusts. The sensor would activate a warning light in the cockpit.

LIDAR

LIDAR, short for Light Detecting and Ranging, uses light waves in the form of a laser beam much like Doppler radar uses radio waves. Instead of measuring the speed of raindrops, it measures the speed of aerosols and dust particles in the atmosphere to detect changes in the wind.

Source: "Making the Skies Safe From Windshear," *NASA Facts On-Line,* June 1992 (NASA Photo L-92-6965)

Figure 3–19. On-Board Wind Shear Warning Systems

the stresses placed on the spacecraft to a level beyond its design capability. Although the Rogers Commission officially dismissed wind shear as a contributing cause of the 1986 accident, NASA has increased its level of monitoring of wind shear in the launch pad area.[92]

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[92] "New Theory on Challenger Disaster," *The Washington Times,* July 8, 1987, reproduced in *NASA Current News,* 87-126; Trudy E. Bell, "Windshear Cited as Likely Factor in Shuttle Disaster," *The Institute of Electrical and Electronics Engineers, Inc.,* May 1987.

Lightning

Lightning is another weather-related phenomenon encountered by aircraft. The effect of lightning strikes on modern aircraft became better understood as a result of a series of flight tests at Langley Research Center during the 1980s. In the Storm Hazards program, which ran from 1980 through 1986, a specially instrumented F-106B jet was repeatedly flown into thunderstorms at various altitudes. The aircraft sustained more than 700 direct lightning strikes during nearly 1,500 storm penetrations.

Newer aircraft made increasingly of composite material did not have the lightning protection provided by older aluminum skins unless they had special conductive fibers embedded during construction. The F-106B examined a variety of protective measures, such as aluminum paint, wire mesh, and diverter strips, while it collected data on lightning and its relationship to other storm hazards.

Icing

Icing is the solidification of moisture that develops on parts of the aircraft, such as the wings, tails, and propellers, in extremely cold weather conditions. Icing usually occurs between ground level and an altitude of 6,100 meters. During World War II, the United States lost more than 100 planes because of icing. Responding to a need expressed by the Army Air Forces and aircraft manufacturers, the National Advisory Committee for Aeronautics (NACA) directed that an Icing Research Tunnel (IRT) be added to the Altitude Wind Tunnel, then under construction at the Aircraft Engine Research Laboratory, the former name of Lewis Research Center (now Glenn Research Center). The first icing test took place there in June 1944.

The IRT is the world’s largest refrigerated icing tunnel. It resembles other subsonic wind tunnels in that a wing or other aircraft component placed in the test section can be subjected to various airspeeds, with the airflow being created by a motor-driven fan. However, the IRT has several unique features. To simulate the aircraft icing environment, a heat exchanger and a refrigeration plant to achieve the desired air temperatures and a spray system to generate a cloud of microscopic droplets of unfrozen water were added. The IRT can duplicate the icing conditions (liquid water content, droplet size, and air temperature) that aircraft might encounter, study factors that cause icing, and test proposed anti-icing and de-icing systems.

The advent of jet engines reduced the demand for the facility, and NASA considered closing it. However, new technology and aircraft design and rising fuel costs increased the demand for new ice protection systems. In 1978, NASA re-instituted an icing research program to address the needs for new and future aircraft designs. The facility underwent a $3.6 million renovation in 1986 to cope with its increased workload and to expand its capabilities. In 1987, the American Society of Mechanical

Engineers designated the IRT an "International Historic Mechanical Engineering Landmark" for its leading role in making aviation safer.

The goal of NASA's icing research was to increase the effectiveness of existing ice protection systems and develop advanced concepts for both anti-icing and de-icing systems that were reliable, cost effective, energy efficient, lightweight, and easy to maintain. Researchers paid particular attention to the needs of small planes and helicopters because many of their flights took them into potential icing environments.

One major goal centered on creating computer codes to predict icing and its effects on airfoils and then to validate those predictions experimentally in the IRT and in flight. Lewis Research Center's overall ice accretion code, called LEWICE, approached the question by calculating the flow field around the airfoil and then applying a droplet trajectory code to compute water movement within the flow. An ice accretion code then determined how much of the incoming water would freeze over a specified period. The IRT was used to grow ice accretions on a wide spectrum of fixed-wing and rotorcraft airfoils, as well as engine inlets. Lewis also flew a DHC-6 Twin Otter aircraft equipped with a stereoscopic camera system to photograph ice formations, as well as several standard instruments to measure ice cloud properties.

Crash Survivability

NASA's 1984 Controlled Impact Demonstration program was designed to improve the survivability of crash victims through reducing postcrash fire hazards and improving crash impact protection. The FAA had been evaluating an anti-misting jet-fuel additive that seemed capable of preventing fuel fires in airplane crashes with promising laboratory test results. However, before publishing a "Notice of Proposed Rulemaking" as a first step toward requiring the additive in certain types of jet aircraft, the agency wanted to test the additive in a real airplane crash.

The FAA conducted the test at NASA's Dryden facilities on an old Boeing 720 jetliner with remote controls. The vehicle was fueled with the anti-misting fuel and guided to a remote location on the Rogers Dry Lakebed. The FAA embedded iron posts in the ground to ensure that the fuel tanks would be ripped open. However, upon impact, the plane burst into flames. Plans to use the anti-misting fuel were dropped.[93]

Related research studied how airplanes crash in the hope of finding some basic structural or other design changes that would increase the survivability of crew and passengers in an accident. NASA acquired several small planes that had been condemned as not airworthy because of flood damage but were suitable for research. It deliberately crashed these single- and twin-engine light planes in a carefully controlled, instrumented, and documented series of impacts. Researchers used extensive instru-

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[93] Wallace, *Flights of Discovery,* pp. 150–51.

mentation inside the aircraft as well as photography outside the planes to acquire data and to document the crashes. They harnessed dummies in crew and passenger positions and assessed their chances of surviving the crashes. These investigations examined energy-absorbing aircraft seat designs and structural design techniques to modify the fuselages to increase their strength and how the progressive destruction of the airframe moved from the point of impact throughout the structure.

Space Research and Technology Programs

Although the space research and technology program also served the needs of non-NASA civil, commercial, and military users of space, the program related more directly to NASA's own priorities than its aeronautics activities. The aeronautics efforts frequently served to further industry's or the military's technology goals as well as NASA's and were often conducted jointly with other agencies or industry. The space research and technology program focused the following:

- Advancing the technology base
- Maintaining technical strength in the scientific and engineering disciplines
- Developing more capable, less costly space transportation systems and large space systems with growth potential
- Promoting scientific and planetary exploration
- Improving understanding of Earth and the solar system
- Supporting the commercial exploitation of space

The program greatly contributed to the Space Shuttle program, developed technologies to be used for the Space Station program, and conducted research into a variety of technological areas with applications in diverse fields. All NASA centers participated in the space research and technology program, and there was significant industry and academic participation.[94]

The program consisted of two parts: the research and technology base program and the focused technology program. The research and technology base program comprised particular disciplines, represented by the divisions, and system technology studies in the areas of propulsion, space energy conversion, aerothermodynamics, materials and structures, controls and guidance, automation and robotics, human factors, computer science, sensors, data systems, and communications.[95]

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[94] Where no source is specifically cited, information in this section comes from the *Aeronautics and Space Report of the President,* issued annually by NASA.

[95] OAST's division names changed frequently during the 1979–1988 period to reflect their predominant focus. While some of the major headings in this section are also division titles, not all are. Rather, these headings are more descriptive of the types of activities that took place.

In the focused programs, technologies were developed for specific applications, and products were delivered in the form of demonstrated hardware, software, and design techniques and methods. Focused development was most often based on the identified needs and potentials of both current and future programs and missions. Spaceflight experiments carried out aboard the Shuttle were an example of focused development. In addition, the Civil Space Technology Initiative, initiated in 1987, and the Pathfinder program, established in 1988, were focused programs.

The Civil Space Technology Initiative was designed to conduct research in technologies to enable efficient, reliable access to operations in Earth orbit and to support science missions. Its technology focused on space transportation, space science, and space operations. The space transportation thrust centered on providing safer and more efficient access to space. It was involved with the design of a new fleet of space vehicles, including new expendable and partially reusable cargo launch vehicles, fully reusable crewed vehicles, and expendable and reusable space transfer vehicles.

The space science area supported more effective conduct of scientific missions from Earth orbit. Technical programs initiated to address the requirements of future long-term missions included high rate/capacity data systems, sensor technology, precision segmented reflectors, and the control of flexible structures. The technologies to enhance future space operations were designed to lead to increased capability, substantial economies, and improved safety and reliability for ground and space operations. Space operations addressed the technologies of telerobotics, system autonomy, and power.

The Pathfinder program began in 1988. It implemented the new National Space Policy that directed NASA to start planning for potential exploration missions beyond the year 2000.[96] The program aimed at developing technologies that would be required for missions that expanded human presence and activities beyond Earth's orbit into the solar system. Without committing to a specific mission at the current time, the program would focus on developing a broad set of technologies that would enable future robotic or piloted solar system exploration missions. The Pathfinder program called for a significant amount of automation and robotics research on developing a planetary rover that would act semi-autonomously in the place of humans on the Moon and Mars. The rover would effectively be a mobile laboratory with its own instrumentation, tools, and intelligence for self-navigation and rock sample acquisition and analysis.[97]

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[96] The White House, Office of the Press Secretary, "The President's Space Policy and Commercial Space Initiative to Begin the Next Century," Fact Sheet, February 11, 1988, reproduced in Appendix F-2 of the *Aeronautics and Space Report of the President, 1988 Activities,* pp. 194–96.

[97] "NASA Information Sciences and Human Factors Program, Annual Report, 1988," NASA Technical Memorandum 4126, July 1989, p. 1.

Space Shuttle Development and Support

Early in the Space Shuttle development stage, NASA's lifting-body program, carried out by OAST, provided data that helped select the shape of the orbiter and simulated the landing on the dry lakebed at Edwards Air Force Base. Two of the final landings represented the types of landings that Shuttles would begin making and verified the feasibility of precise, unpowered landings from space.

Data from each lifting-body configuration contributed to the information base NASA used to develop the Shuttles and helped produce energy management and landing techniques used on each Shuttle flight. Lifting-body data led to NASA's decision to build the orbiters without airbreathing jet engines that would have been used during descent and landing operations and that would have added substantially to the weight of each vehicle and to overall program costs.

Because the same airbreathing engines that were eliminated would also have been used to ferry the Shuttle from the landing site back to the launch site, NASA devised the concept of a mothership to carry out the ferry mission. The Boeing 747 Shuttle Carrier Aircraft (SCA) evolved from recommendations by Dryden engineers. The SCA launched the prototype orbiter *Enterprise* during the approach and landing tests in 1977 and has been the standard ferry vehicle since the first Shuttle was launched. (A second 747 was added in 1990.)

The approach and landing tests conducted in 1977 verified orbiter approach and landing characteristics and subsonic airworthiness. The tests revealed a problem with pilot-induced oscillation that was described in the "Aeronautics Research and Technology Programs" section of this chapter. The approach and landing test program also verified that the orbiters could be carried safely on top of the SCA.

OAST also was responsible for the development of the Shuttle's thermal protection system, the solid rocket booster recovery system, flight control system computer software, tests and modifications to the landing gear and braking systems, and, in the 1990s, the drag parachutes that were added to *Endeavour*. In 1977 and 1978, NASA's B-52 was used to test the solid rocket booster parachute recovery system, which allowed empty booster casings to be recovered and reused.[98]

In 1980, using F-15 and F-104 aircraft, NASA pilots flew sixty research flights to test the Space Shuttle's thermal protection tiles under various aerodynamic load conditions. The test tiles represented six locations on the orbiter and were tested up to speeds of Mach 1.4 and dynamic pressures of 1,140 pounds per square foot. The local tests led to several changes to improve bonding and attachment techniques.[99]

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[98] "B-52 Launch Aircraft," *NASA Facts On-Line,*" FS-1994-11-005-DFRC, Dryden Flight Research Center, November 1994.

[99] "Dryden Contributions to Space Shuttle Development Many," *The X-Press,* NASA Ames Research Center/Dryden Flight Research Facility, April 5, 1991, p. 2.

Before orbital flights took place, NASA conducted an independent analysis of orbiter design structural loads and handling qualities, drawing on experience from the X-15, YF-12, and lifting-body programs. Although the study revealed some minor design deficiencies, it verified the overall adequacy of design to accomplish a successful orbital reentry. NASA also conducted preflight tests, in the Thermostructures Research Facility at Dryden Flight Research Center, of the elevon seals on orbiter wings to assure that hot free-stream air during control surface movement during reentry would not damage the aluminum wing structure.

The B-52 also served as a testbed for drag chute deployment tests that helped verify the drag chute system being installed on the orbiters. The system would allow orbiters to land on shorter runways and help reduce tire and brake wear.

Space research conducted at Langley Research Center, sometimes in conjunction with research at Dryden, also contributed to the Space Shuttle program. These activities included:

- Developing the preliminary Shuttle designs
- Recommending the modified delta wing for the orbiter rather than a conventional straight wing
- Conducting 60,000 hours of wind tunnel tests and analysis
- Conducting structures and materials tests to determine the requirements for various areas of the vehicle
- Investigating and certifying the thermal protection system for the launch environment
- Performing design, analysis, and simulation studies on the control and guidance systems
- Conducting landing tests on the main and nose gear tires and brake systems
- Conducting a runway surface texture test and recommending runway modifications for the Kennedy Space Center runway
- Participating in the redesign of the solid rocket booster components
- Examining launch abort and crew bailout capabilities
- Defining ascent aerodynamic wing loads[100]

OAST was actively involved in the redesign of the Space Shuttle solid rocket motor field joint following the 1986 *Challenger* accident as part of its materials and structures program. A significant part of this effort was directed toward developing a test procedure for qualifying candidate O-ring materials, and a test method was established as the standard for O-ring materials.

The Shuttle's landing gear and tires were another area of investigation. The Shuttle was equipped with four small wheels, two on each main

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[100] "NASA Langley Research Center Contributions to Space Shuttle Program," *NASA Facts*, Langley Research Center, March 1992.

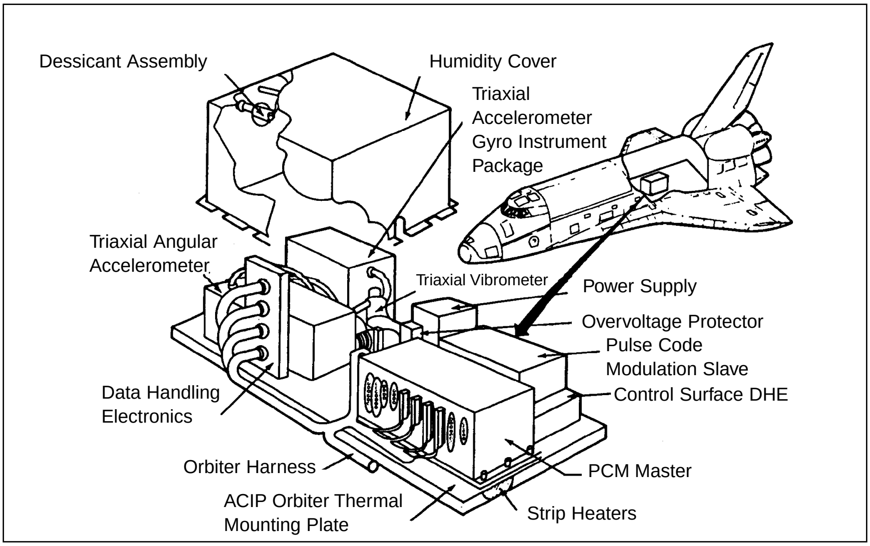

Figure 3–20. Aerodynamic Coefficient Indentification Package (ACIP) Experiment

gear. This contrasted with the eight to sixteen wheels that a commercial airliner of similar weight would have. The difference was because of the extreme temperatures the Shuttle encountered and the difficulty of protecting the landing gear and tires. NASA used the Convair 900 aircraft to test the Shuttle's landing gear components and to learn about tire wear on the Shuttle.

The Space Shuttle as a Research Facility

The Space Shuttle also served as an in-space laboratory to test many of OAST's basic research and technology concepts and to validate technology in the space environment. NASA used the Shuttle as an experimental facility for research in aerodynamics, thermal protection systems, and the payload environment. These included the Orbiter Experiments Program, the OAST-1 payload on STS 41-D, the Assembly Concept for Construction of Erectable Space Structures (ACCESS) and the Experimental Assembly of Structures in Extravehicular Activity (EASE) on STS 61-B, and the Long Duration Exposure Facility (LDEF) on STS 41-C.

Orbiter Experiments Program

The Orbiter Experiments Program consisted of a number of experiments on the early Shuttle missions. These experiments gathered data that assessed Shuttle performance during the launch, boost, orbit, atmospheric entry, and landing phases of the mission. The data verified the accuracy of wind tunnel and other simulations, ground-to-flight extrapolation methods, and theoretical computational methods. Table 3–66 lists the experiments, and Figures 3–20, 3–21, 3–22, 3–23, and 3–24 each depict

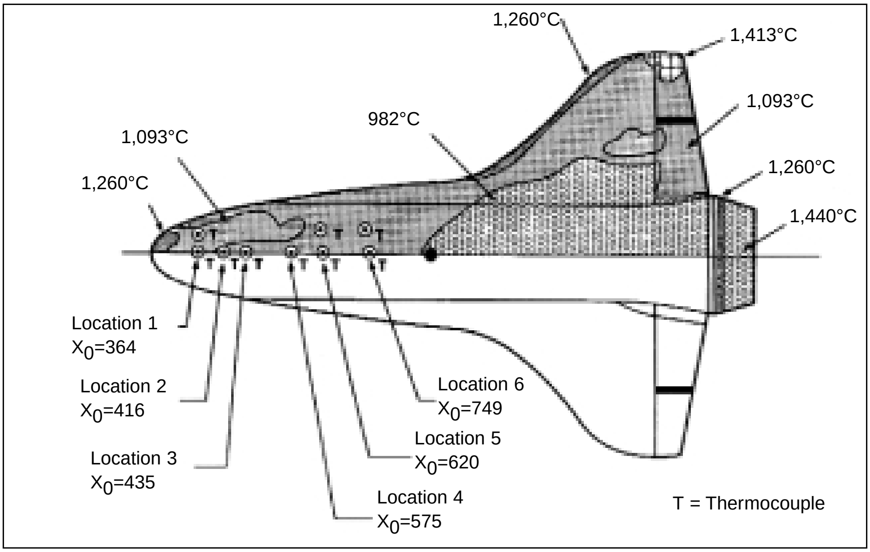

Figure 3–21. Catalytic Surface Effects (CSE) Experiment (Lower Surface View)

one of those experiments. Additional information on the Orbiter Experiments Program can be found in Chapter 3, "Space Transportation/Human Spaceflight," in Volume V of the *NASA Historical Data Book.*

OAST-1

OAST-1 was the primary payload on STS 41-D, which was launched August 30, 1984. Mission objectives were to demonstrate the readiness

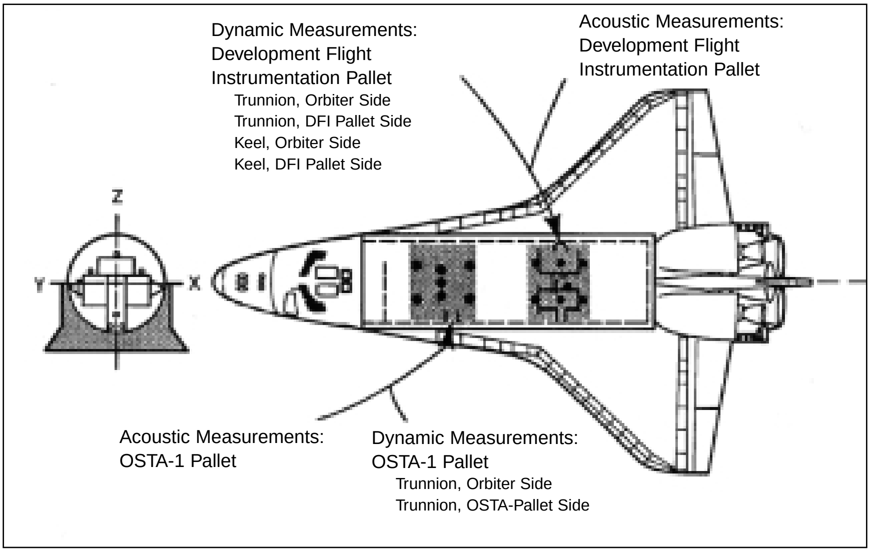

Figure 3–22. Dynamics, Acoustic, and Thermal Environment (DATE) Experiment

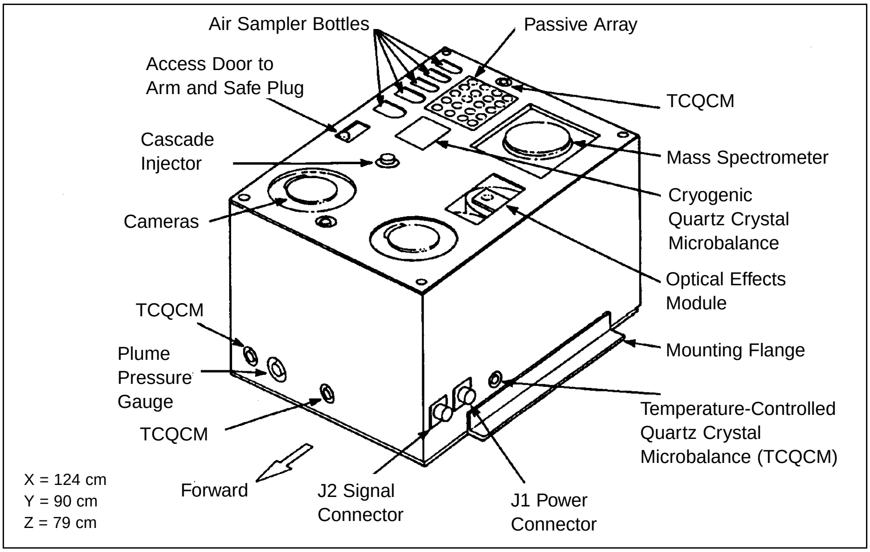

Figure 3–23. Induced Environment Contamination Monitor (IECM)

and determine the performance of large, low-cost, lightweight, deployable/retractable solar array technology, to demonstrate methods to define the structural dynamics of large space structures, and to evaluate solar cell calibration techniques as well as calibrate various types of solar cells. OAST-1 demonstrated the first large, lightweight solar array in space that could be restowed after it had been deployed.

The crew operated OAST-1 from the aft flight deck of the orbiter. The payload carrier was a triangular, truss-like mission support structure that spanned the width of the orbiter cargo bay. The payload consisted of three

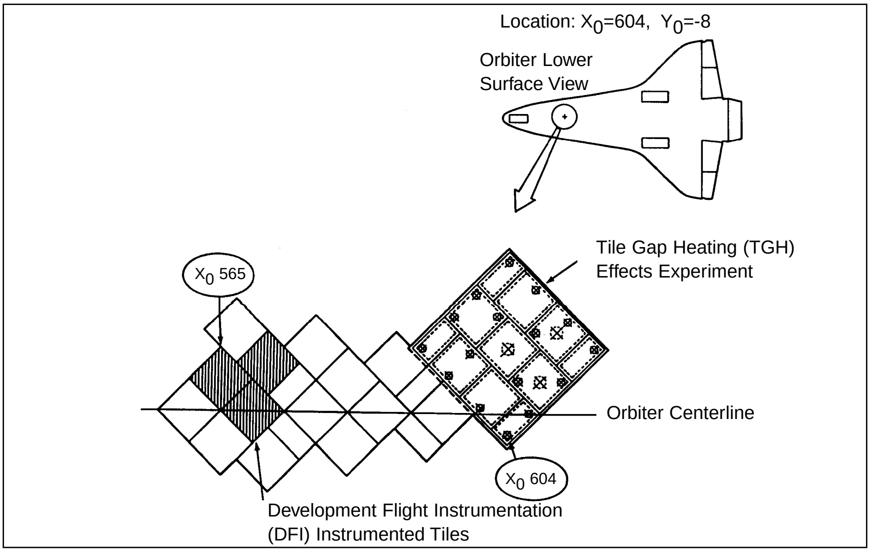

Figure 3–24. Tile Gap Heating (TGH) Effects

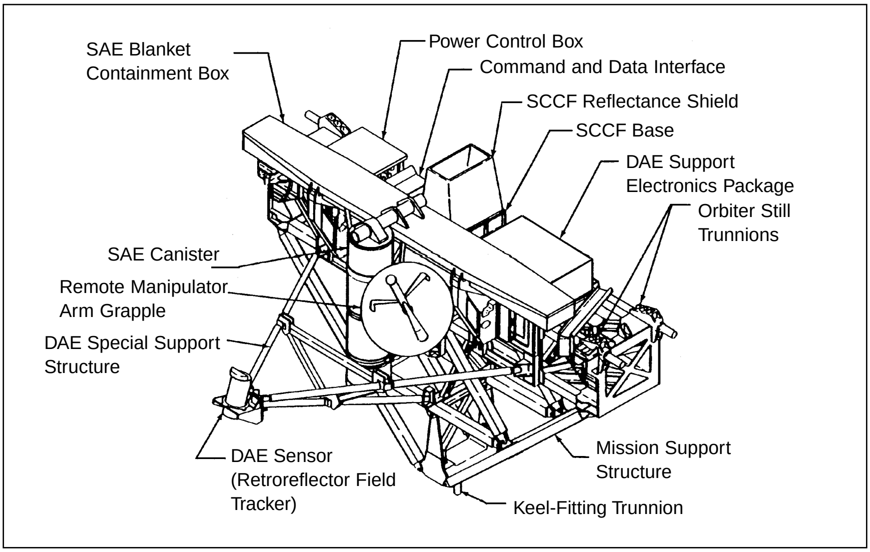

Figure 3–25. OAST-1 Payload Elements
(The OAST-1 payload consisted of three experiment systems that investigated solar energy and large space structures technology, both of which would be vital parts of a space station.)

major experiments and associated equipment: the Solar Array Experiment (SAE), the Dynamic Augmentation Experiment (DAE), and the Solar Cell Calibration Facility (SCCF). Figure 3–25 illustrates the OAST-1 payload elements.

The SAE demonstrated the properties and capabilities of the solar array. The Shuttle crew extended and retracted the solar array several times during the mission and gathered data on system performance. The experiment also measured deflections and bending motions on the fully deployed solar wing and gathered solar cell performance data. The solar array consisted of eighty-four panels and could fold flat. When fully extended, it rose more than ten stories above the cargo bay. When stored for launch and landing, the array folded into a package only seventeen centimeters thick.

The DAE gathered data to validate an on-orbit method to define and evaluate the dynamic characteristics of large space system structures. The SCCF evaluated and validated solar cell calibration techniques then used by the Jet Propulsion Laboratory under contract to NASA. This validation compared the performance of cells on orbit in the facility with the performance of the same cells flown on a high-altitude balloon test flight.

Long Duration Exposure Facility

The Long Duration Exposure Facility (LDEF) was a passive, free-flying reusable structure that accommodated experiments requiring long-term exposure to space. Launched from STS 41-C on April 7, 1984, it was retrieved by STS-32 in January 1990, after nearly six years of service, long after the original plan that had called for retrieval after a useful lifetime of approximately ten months. LDEF was funded by OAST's Systems Technology Program.

The Space Shuttle *Challenger* deployed LDEF on the second day of the mission. Astronaut Terry Hart used the Shuttle's 15.2-meter-long remote manipulator arm to engage LDEF and maneuver it out of the payload bay. In the process, a startup signal was sent to electrical systems in the experiments. To move away from LDEF, the Shuttle fired small thrusters.

LDEF carried fifty-seven experiments in eighty-six desktop-sized, open aluminum trays arrayed around the surface of LDEF. Seventy-two experiments were located around the circumference of the facility; six were on the Earth-pointing end and eight on the space-pointing end. Together, all of the trays and their experiments weighed only 6,078 kilograms. The total weight of the structure, trays, and experiments was 9,707 kilograms. The experiments carried more than 10,000 specimens that gathered scientific data and tested the effects of long-term space exposure on spacecraft materials, components, and systems.

All the experiments required free-flying exposure in space but needed no extensive electrical power, data handling, or attitude control systems. The facility was designed to use gravity to be inherently stable in orbit. Thus, an experiment would keep a single orientation with respect to the orbit path. This allowed improved postflight data analysis because impacts and other space environment effects would differ for various orientations. In addition, the constancy of LDEF's drag as it moved through the uppermost traces of Earth's atmosphere also enhanced postflight data analysis.

The experiments fell into four groups: materials and structures, power and propulsion, science, and electronics and optics. They involved 194 principal investigators, representing sixteen U.S. universities, thirteen private companies, eight NASA centers, eight DOD laboratories, and thirty-four similar research organizations in Canada, Denmark, the Federal Republic of Germany (former West Germany), France, Ireland, The Netherlands, Switzerland, and the United Kingdom. NASA designed and built LDEF at Langley Research Center. NASA provided experiment trays to investigators, who built their own experiments, installed them in trays, and tested them.

LDEF had no central power system. Experiments that required power or data recording systems provided their own, although NASA made its Experiment Power and Data System available to investigators. The experiment initiation system, triggered by the orbiter's remote manipulator system, was the only electrical connection between LDEF and the active experiments.

Although LDEF carried a broad range of scientific and technological investigations on this mission, NASA first conceived of it solely as a meteoroid and exposure module (MEM). Langley Research Center proposed MEM in 1970 as the first Shuttle payload. MEM was foreseen as a cylinder sized for the Shuttle's payload bay. The Shuttle would place it in orbit, where its large surface area would collect a comprehensive sample of meteoroid data. MEM was to include thick-skin, thin-skin, and bumper configurations. After several months, the Shuttle would retrieve MEM and return it to Earth for data analysis.

In 1974, MEM was renamed LDEF, and LDEF officially became a NASA project managed by Langley Research Center for OAST. Meteoroid research was still seen as the primary mission. Eventually, however, LDEF also became a vehicle for many other types of studies, tests, and evaluations. Table 3–67 gives a brief chronology of LDEF project development. Table 3–68 describes the facility and mission characteristics.

Access Concept for Construction of Erectable Space Structures

The ACCESS experiment, which flew on STS 61-B along with the Experimental Assembly of Structures in Extravehicular (EASE) activity (launched November 26, 1985), gave astronauts the opportunity to erect the type of structure that would be used for the Space Station. Working in the payload bay at fixed workstations, crew members assembled small components to form larger structures during two spacewalks.

The structure consisted of ninety-three tubular aluminum struts, each 2.54 centimeters in diameter. Thirty-three were 1.37-meter-long struts; sixty were 1.8-meter-long diagonal struts; thirty-three were identical nodal joints; nine struts were used within and between bays; and six struts joined at one node. Once assembled, the structure was 13.7 meters high.

Langley Research Center developed ACCESS and worked with Marshall Space Flight Center in designing both ACCESS and EASE, developing assembly methods in ground-based and neutral buoyancy simulations, as well as assisting in crew training. Following the on-orbit experiment, the ACCESS experiment was repeated in a ground-based laboratory using a teleoperated manipulator. In this demonstration, the teleoperated manipulator system was substituted for one of the astronauts, while a technician assumed the role of the other astronaut. The demonstration proved that current manipulators had sufficient dexterity to assist the flight assembly of Space Station structures.

Experimental Assembly of Structures in Extravehicular Activity

EASE was a geometric structure that resembled an inverted pyramid. It was composed of a small number of large beams and nodes. When completely assembled, the structure was 3.7 meters high. The Massachusetts Institute of Technology developed the structure along with Marshall Space Flight Center. Crew members moved about the payload bay while assembling this structure.

Space Station Development

Many of OAST's space research and technology activities had direct application to Space Station development. Its materials and structures program worked to develop durable materials and design structures that could be erected and serviced in space. OAST provided data to support NASA's selection of the dual-keel configuration for the Space Station. The primary areas being investigated were lightweight structural members, packaging techniques, structurally predictable behavior, and reliable deployment. Its work in developing the technology base for high-performance, long-life power systems also had direct application to the power requirements of the Space Station.

The space human factors program focused on verifying human performance models in long-term weightless conditions such as those that would be encountered in assembling and operating the Space Station. Extravehicular activity (EVA) would be an important part of Space Station operations. OAST gathered quantitative data on the effects of types of spacesuits that could be used for EVA on human capabilities and productivity.

Other Space Research and Technology Activities

In addition to the activities already described, other major space research and technology activities are summarized below.

Space Energy Conversion

This area of research developed the technology base for high-performance, long-life power systems for space applications. It included research in the areas of solar power, space nuclear reactor power systems, batteries, and thermal systems.

In the area of solar power, OAST worked to define the effects of the space environment on space power systems. A space test evaluated the power loss and breakdown phenomena of photovoltaic systems as voltage levels and area varied.[101] This information would be used to correlate interaction phenomena measured in space and ground tests for eventual design guidelines for high-power space systems in low-Earth orbit.

In 1982, researchers identified components that could potentially revolutionize solar cell energy conversion, increasing efficiencies from 16 percent to as much as 50 percent. These concepts included coupling sunlight into the electronic surface charge density, cascading solar cell

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[101] Photovoltaic describes a technology in which radiant energy from the Sun is converted to direct current electricity. U.S. spacecraft first used photovoltaic cells for power in 1958 (Photovoltaic Systems Assistance Center, U.S. Department of Energy).

junctions for selective spectral utilization, and exploiting the unique properties of the photo-active protein rhodopsin.

Work also continued on high-capacity energy storage for long-range missions. Researchers tested the breadboard model of a solid-polymer-electrolyte fuel-cell-electrolysis system. An alternate energy storage system based on electro-chemistry demonstrated an efficiency of 82 percent over 100 simulated day-night cycles in low-Earth orbit. This technology could reduce the weight of energy storage systems by one-half.

Researchers achieved significant improvements in the power per kilogram, cost, and efficiency of solar array power systems. In the area of low-cost solar arrays, researchers designed, fabricated, and tested a miniature Cassegrain concentrator with a concentration ratio of 100. This had the potential for reducing array costs to about $30 per watt, about one-twentieth the then-current cost.

In 1985, researchers made significant progress in solar cell and solar array technology to improve conversion efficiency, reduce mass and cost, and increase operating life. Over 20 percent conversion efficiency was demonstrated for gallium-arsenide thick-cell technology. Tests of thin-cell gallium arsenide verified cell efficiency exceeding 14 percent.

In 1987, researchers fabricated indium phosphide solar cells—a type that combines good performance and efficiency with improved tolerance to natural radiation. In geosynchronous orbit, conventional silicon solar cells can lose up to 25 percent of their output during a seven-year life. In the radiation belts in low-Earth orbit, the loss can be as high as 80 percent. Measurements showed indium phosphide cell efficiency to be essentially unaffected by natural radiation. This meant that future solar arrays could be smaller and lighter by eliminating the need for oversized systems to accommodate efficiency losses caused by radiation damage.

During the 1980s, NASA participated in the joint Space Nuclear Reactor Power System with the Department of Energy and DOD. Established in 1981, the jointly funded and managed program focused on the barrier technologies for space nuclear reactor power systems. Relating to dynamic energy conversion systems that could be used with the SP-100 nuclear reactor, the program investigated developing space power systems for future lunar and Martian bases. Researchers believed that outer planetary missions could be accomplished using a 120-kilowatt uranium-oxide-fueled reactor and silicon-germanium thermoelectric converters. Related research evaluated thermoelectric, thermionic, and Stirling cycle conversion systems.

In 1985, the Technology Assessment and Advancement Phase (Phase I) of the program was completed. The recommendation that the thermoelectric reactor power system concept be the baseline was approved. The partners executed a memorandum of agreement for Phase II of the program on October 8, 1985. The program also saw significant progress in free-piston Stirling energy conversion technology. In 1987, a 25-kilowatt, free-piston Stirling demonstration engine, the largest of its kind in the world, was built and tested.

More than 95 percent of NASA's Earth-orbiting spacecraft used nickel-cadmium batteries. Increasing the lifetime of these batteries would increase the operating lifetime of many satellites. During 1980, OAST's researchers developed methods to double the operational lifetime of the batteries by developing a technique of deep-discharge reconditioning.

In 1985, researchers were able to change the chemistry and design of nickel-hydrogen batteries, which resulted in a sixfold increase in the cycle life and seemed promising at meeting the 50,000-cycle requirement of systems in low-Earth orbit. As a result of these advances, nickel-hydrogen batteries became a prime candidate for energy storage on the Space Station and on other scientific platforms.

Materials and Structures

This area of research focused on improving the safety of existing vehicles and advancing the technology for future spacecraft, large-area space structures, and advanced space transportation systems. In 1983, a space-environmental-effects facility became operational at Langley Research Center. The facility could simulate the space environment to study effects on materials. It provided ground-based evaluation of the long-term environmental effects of space on materials and helped in developing new materials and protection techniques. The facility allowed for the testing of composite materials and for the observation of changes in structural properties.

This Materials and Structures Division at Langley had a large role in developing and improving thermal protection materials for use on the Space Shuttle. In 1981, the development of advanced ceramic tile made from a new material—fibrous, refractory, composite insulation—promised to offer lower cost, more durable protection. The addition of aluminum borosilicate fibers to the silica fiber already in use formed a new material with unique physical, mechanical, and thermal properties. It had greater strength, greater resistance to damage, and would save approximately 500 kilograms in the weight of each orbiter.

In 1982, laboratory tests demonstrated that another new, low-cost material could increase the life and durability of the orbiter's thermal protection shield. This advanced, flexible, and reusable surface insulation was a quilt-like sandwich with silica on the outside and microquartz felt in the middle. The layers, which were sewn together in the middle to form 2.54-centimeter squares, were for temperatures less than 650 degrees Centigrade. The use of advanced, flexible, and reusable surface insulation on the lee side of the orbiter offered more tolerance to damage, easier maintenance, and lower installation costs than the tiles then in use. In 1984, 2,300 flexible woven ceramic blankets replaced 8,000 existing ceramic tiles on the orbiter *Discovery.*

The Materials and Structures Division also continued investigating advanced thermal protection materials intended for future space transportation systems, such as the Orbital Transfer Vehicle. Silica and silicon carbide (Nicalon) fibers were woven in three-dimensional fabrics for the high-temperature thermal protection system applications required by these vehicles. A chemical vapor deposition approach also showed great promise for producing high-performance ceramic composite thermal protection systems.

Following the *Challenger* accident, the Materials and Structures Division was actively involved in the redesign of the solid rocket motor field joint. It established a test method for qualifying candidate O-ring materials and involved three tests: a resiliency test, a vibrational damage-resistance test, and a test that simulated in-situ conditions, including temperature, gas pressure, and controlled gap closure.

Propulsion

This discipline area focused on developing advanced propulsion systems. The systems were to be used in Earth-to-orbit ascent and planetary transfer vehicles and for orbiting spacecraft auxiliary propulsion systems. Its research emphasized high-performance and extending component life, thus extending maintenance intervals. Researchers developed cooling techniques that were tailored specifically to rocket engines as an alternative to cooling turbine blades with hydrogen fuel, which had proved inadequate. They developed a cryogenic engine-bearing model to determine cooling, lubrication, and bearing design characteristics. Another new model predicted the life of materials subjected to both low-cycle and high-cycle fatigue.

Orbital transfer propulsion research focused on developing high-performance, high-pressure, variable thrust engines that would be stored and fueled in space. Propulsion studies in conjunction with the analysis of orbit transfer vehicle systems indicated that multiple high-performance, low-thrust engines with 13,464 to 33,660 newtons of thrust were appropriate and cost-effective for a space-based, aero-assisted vehicle.

Electrical propulsion research focused on resistojets, arcjets, ion, and magnetoplasmadynamic (MPD) thrusters. In the Auxiliary Propulsion program, researchers determined that electric-powered thrusters known as arcjets offered more than twice the energy level per unit of fuel than conventional chemical systems provided. Arcjet technology objectives included developing high-temperature materials resistant to the electric arc and designing concepts for higher efficiency and longer life. A 1985 memorandum of agreement between NASA and the U.S. Air Force coordinated research activities of the two organizations, and several tests of the Air Force thirty-kilowatt arcjets were conducted in NASA laboratories.

MPD propulsion technology could become an option when megawatt power was available from nuclear power systems. MPD technology was capable of developing the highest specific impulse and relatively high thrust. A main technology goal was long-life cathodes capable of resisting erosion caused by intense heat (more than 1,650 degrees Celsius) and electric plasma. During 1985, tests in an MPD simulator demonstrated that there was less erosion at higher power than at low, indicating electron cooling effects. Compared to chemical systems, the MPD thruster proposed for advanced propulsion systems could potentially provide a two- to fourfold reduction in propellant mass. An MPD thruster was tested that had many advantages as a space propulsion system, being both simple in concept and compact in size.

Automation and Robotics

The Automation and Robotics program was established in FY 1985 in response to congressional interest in the Space Station and to reduce costs and increase the performance of future missions. It developed and demonstrated technology applicable to the Space Station, orbital maneuvering vehicle, orbital transfer vehicle, mobile remote manipulator system, and planetary rovers. The program accomplished major research goals in the areas of operator interface, systems architecture and integration, and planning and reasoning.

The Automation and Robotics program consisted of the Telerobotics program and the Autonomous Systems program. The Telerobotics program achieved its first major technology demonstration through the vision-based de-spin of a spinning satellite (once it was initialized by a human-guided graphic overlay). The Beam Assembly Teleoperator demonstrated three applications: assembling beam elements into a space structure, using a general control structure for coordinated movement of multiple robot arms; and using the Oak Ridge National Laboratory's teleoperated manipulator to recreate the ACCESS experiment.

The Autonomous Systems program moved toward the Space Station Thermal Control Expert System technology demonstration. The program developed an operational readiness prototype expert system for monitoring Space Shuttle communications systems. The program also developed an expert system for aiding the communications officer in the Shuttle Mission Control Room, which was first operational on STS-26 in 1988.

Communications

The objective of the Communications Technology program was to enable data transmission to and from low-Earth orbit, geostationary orbit, and solar and deep space missions. It represented three major research and development discipline areas: microwave and millimeter wave tube components, solid-state monolithic integrated circuits, and free space laser communications components and devices. Its activities ranged from basic research in surface physics to generic research on the dynamics of electron beams and circuits. Researchers investigated advanced semiconductor materials devices for use in monolithic integrated analog circuits, the use of electromagnetic theory in antennas, and the technology needed for the eventual use of lasers for free space communications for future low-Earth, geostationary, and deep space missions that required high data rates with corresponding directivity and reliability.[102]

In 1982, researchers developed the first sixty-gigahertz, low-noise receiver for spacecraft data transfer systems and completed development of a solid-state sixty-gigahertz power amplifier. This would permit high-transfer rates of large quantities of data in millimeter-wave intersatellite communications links—an important characteristic of an advanced, fully integrated ground-to-space communications system. In 1984, researchers demonstrated, for the first time, technology for a fifty-five-meter, offset wrap-rib antenna that would support a nationwide mobile communications system.

Advanced Communications Technology Satellite

OAST developed the fundamental technologies for the experimental Advanced Communications Technology Satellite (ACTS), funded and managed by NASA's Office of Space Science and Applications (see Chapter 2). The satellite demonstrated the critical communications technologies that would be needed for high-capacity operational satellites in the 1990s.

ACTS was a high-capacity domestic communications satellite operating in the Ka-band frequencies (thirty/twenty gigahertz) and was called the "switchboard in the sky." Performing in a largely untapped area of the frequency spectrum, the frequency bandwidth for ACTS in the Ka-band was twice the size of the C-band and Ku-band combined, thereby yielding a greatly increased satellite capacity.[103]

Hardware developments leading up to ACTS began in 1980 with NASA's thirty/twenty gigahertz program. It marked NASA's return to the communications field after an absence that began in 1973. The program formally began in 1984, and launch took place in 1993.

OAST's contributions to ACTS included a multibeam antenna with both fixed and scanned beams that could provide 100 times more power and ten times more bandwidth than other satellite systems. The antenna could produce three stationary and two hopping beams, with each beam encompassing an area approximately 250 kilometers in diameter. The ability to space the beams across expanses of territory allowed the use of the same frequency in many beams, which was called frequency reuse. The use of these high frequencies made wide bandwidth channels available. The satellite also featured a baseband processor, a high-speed programmable switch matrix, a traveling wave tube amplifier, and a low noise receiver.

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[102] "NASA Information Sciences and Human Factors Program," p. 29.

[103] "Future Satellites to Carry Advanced Technologies," *Space News,* October 22–28, 1990, p. 18.

Computer Science

The Computer Science program was established in 1982 to adapt supercomputer technology, human computer interfaces, and artificial intelligence to aerospace applications, to advance computer technology where NASA requirements push the state of the art, and to provide advanced computational facilities for aerospace research. The program worked at improving knowledge of fundamental aerospace computing principles and advancing computing technology in space applications such as software engineering and information extraction from data collected by scientific instruments in space. Emphasis was placed on producing highly reliable software for critical space applications.

The program included the development of special algorithms and techniques to exploit the computing power provided by high-performance parallel processors and special-purpose architectures. Important areas included computational fluid dynamics, computational chemistry, structural analysis, signal processing, and image processing.

Work in the area of the fundamentals of database logic resulted in the development of a common user interface for accessing data from several databases, even when the databases had very different structures. This work provided the foundation to allow NASA space data users to access multiple databases independently of their physical distribution or structure. It would reduce the cost of investigations and enable database-intensive scientific research that would otherwise be unaffordable.[104]

Researchers in the program were also developing a reconfigurable, fault-tolerant architecture for a space-borne symbolic processor. This effort included addressing the issues of software development environment versus run-time environment, dynamic database maintainability, and an operating system for efficient use of the multiprocessor architecture.

In 1982, researchers developed an experimental computer program for automatically planning and scheduling spacecraft action sequences. The program combined, for the first time, artificial intelligence technology with operations research and discrete-event simulation techniques to perform automatically tasks that usually required many mission operations personnel. Later, in 1984, NASA realized major performance improvements in an automated planning program called DEVISER, which used artificial intelligence techniques to plan and schedule spacecraft operations automatically. The planning system, which was tailored for use by the Voyager spacecraft during its encounter with Uranus, exhibited sufficiently high levels of sophistication and capability for realistic planning of major mission sequences involving as many as 100 distinct tasks.

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[104] "NASA Information Sciences and Human Factors Program," p. 65.

Controls and Guidance

This program was directed toward enabling future space transportation systems, large future spacecraft, and space systems to have large communications antennas and high-precision segmented reflector astrophysical telescopes. To address the advanced requirements of future systems and spacecraft, the program focused on providing the generic technology base to support the implementation of advanced guidance, navigation, and control. This technology had the capability to reduce the number of people needed to plan and generate mission software and to later provide for mission control.

The area of computational controls was stressed to develop cost-effective, high-speed, and high-fidelity control system simulation and analysis tools. The thrust of the work was to develop methods and software to enable the analysis and real-time simulation of complex spacecraft for control design certification.[105]

Data Systems

The Data Systems program consisted of research and technology focused on controlling, processing, storing, manipulating, and analyzing space-derived data. The objectives of the program were to provide the technology advancements needed to enable the affordable use of space-derived data, to increase substantially the capability for future missions of on-board processing and recording, and to provide high-speed and high-volume computational systems anticipated for missions such as the Space Station and the Earth Observing System.

The program supported fundamental research in areas such as laser diodes, worked to select and provide the appropriate on-board processor technology for future NASA missions, and supported the development of two flight processors with special architectures. The ongoing support for solid-state laser research led directly to the development of a nine-laser diode array used in the Optical Disk Recorder. The laser research also focused on Space Station data handling applications. Also, the Data Systems program focused on providing processors that would work very reliably in the space environment, including missions in polar orbit and some planetary missions that must operate in high-radiation environments.

The NASA End-to-End Data System (NEEDS) was an OAST major data systems program. NEEDS defined system configurations and developed enabling techniques and technology for the NASA-wide information systems of the 1980s. Studies performed as part of this program concluded that space-acquired data in “packet” form should be an integral part of long-term NASA data system architectures.

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[105] *Ibid.*, p. 127.

Standard packet data would reduce end-to-end data transport costs by allowing a high degree of automation, eliminate the need for unique mission hardware and software for acquisition, staging, and distribution, simplify quality control for all data types, enable deterministic data accountability, allow autonomous instrument formatting, and establish high-level interfaces that were constant throughout the life of an instrument.

One of the major elements of the program was the massively parallel processor (MPP), put into operation at Goddard Space Flight Center in 1983. Built and delivered by Goodyear Aerospace Corporation after four years of development, this "multibillion-operations-per-second" computer consisted of 16,384 processors and was designed for image processing. The MPP permitted modeling of complex space science phenomena not possible with conventional computers. NASA used the MPP for weather and climate modeling and image analysis research.

One of the major applications of the MPP was in the area of image processing from very-high-spatial-resolution image sensors, both active and passive. These sensors generated data at rates up to 10^{13} bits per day, requiring from 10^9 to 10^{10} operations per second for processing. Another application was the assimilation of data for the Global Habitability model that involved the merging of data from various imaging sensors as the Thematic Mapper and the SIR-B synthetic aperture imaging radar and the creation of the images from raw data as required for these sensor systems. Other applications involved signal processor of LIDAR and radar data, infrared and microwave sounder processing, and numerical modeling simulations of climate.[106]

The Advanced Digital Synthetic Aperture Radar (SAR) processor (ADSP) included a special architecture and algorithms to process SAR data. On-board SAR processing was a very challenging technical problem because of the enormous volumes of raw SAR data that the instrument would collect. The Jet Propulsion Laboratory's ADSP, a six-gigaflop processor capable of providing Seasat and SIR-B imagery in real time, was successfully demonstrated in 1986. However, in spite of the successful demonstration, it did not provide the technology required for real-time on-board processing of SAR data because it occupied two meter racks just over two meters and consumed a total of twenty kilowatts. The SAR processor then being developed would use data compression to reduce the data rate and volume problems imposed on the Tracking and Data Relay Satellite System downlink. On-board SAR processing would also allow for the direct downlink of on-board-generated images for users who require images in near real time.[107]

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[106] "Annual Report, 1983," NASA Computer Science and Electronics Program (no page numbers).

[107] "NASA Information Sciences and Human Factors Program," p. 174.

Human Factors

The Human Factors program focused on developing a technology base for intelligent operator interfaces, especially with autonomous subsystems, and developing a new generation of high-performance spacesuits, gloves, and tools and end effectors to meet the requirements of advanced space systems. Crew station research included the development of methods for the astronaut to supervise, monitor, and evaluate the performance of robotic systems, other space subsystems, and orbital vehicles. A fundamental understanding of the human visual and information integration capabilities provided a technical basis to develop mathematical, anthropometric, and graphical models of human interactions with space systems and equipment. Virtual workstation research demonstrated the initial feasibility to perceive, evaluate, and control robotic assistants as well as computer-generated images of actual systems and space structures. This research also could make it possible to interact with these via computer models.

The development of a new EVA spacesuit and gloves was a second major research area. The completion of the AX-5 hard suit and its initial test for mobility and ease of use were major accomplishments. This suit was a prime candidate for use on the Space Station; it allowed the astronaut to don the spacesuit without extensive prebreathing of oxygen. Also under development was a project to study and develop end-effector mechanisms whereby the EVA-suited astronaut could control and supervise robotic assistants. The research program also included the development of new methods to display information on the spacesuit's visor to allow the astronaut to interact with displayed information by means of voice commands.[108] Researchers also designed an ultrawide field-of-view helmet-mounted display for the visual monitoring of remote operations.

Sensor Systems Technology

The Sensor Systems program provided expertise and technology to advance space remote sensing of terrestrial, planetary, and galactic phenomena through the use of electromagnetic and electro-optic properties of gas, liquid, and solid-state materials technology. The research and development part of this program consisted of research on artificially grown materials such as quantum well and superlattice structures, with the potential for new and efficient means for detecting electromagnetic phenomena. Research was also conducted on unique materials and concepts for detector components and devices for measuring high-energy phenomena such as ultraviolet rays, x-rays, and gamma rays that are required observables in astrophysical and solar physics missions. The focused technology part of the program was balanced among the areas of detector sensors, submillimeter wave sensors, LIDAR/differential absorption sensors, and cooler technology.[109]

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[108] *Ibid.*, p. 209.

[109] *Ibid.*, p. 231.

Table 3–1. Total Office of Aeronautics and Space Technology Program Funding (in thousands of dollars)

Year	**Request**	**Authorization**	**Appropriation**	**Programmed (Actual)**
1979	375,400	391,400	*a*	376,400
1980	427,100 *b*	433,700	*c*	426,866
1981	389,500 *d*	410,000	384,750 *e*	384,000
1982	344,000 *f*	414,100	375,800 *g*	375,800
1983	355,000 *h*	408,000	403,000	404,500
1984	439,300 *i*	463,300	440,300	452,300
1985	492,400	502,400	496,000	492,400
1986	522,000 *j*	520,000	522,000	488,657
1987	592,200 *k*	599,200	601,200	625,000
1988	691,000 *l*	687,000	665,000	606,700

a Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

b Amended budget submission. Original budget submission = $419,700,000.

c Undistributed. Total 1980 R&D appropriation = $3,838,500,000.

d Amended budget submission. Original budget submission = $409,500,000.

e Reflected recission.

f Amended budget submission. Original budget submission = $469,000,000.

g Reflected General Supplemental Appropriation of August 13, 1982, which was approved on September 10, 1982.

h Initial budget submission. Revised submission unspecified.

i Revised budget submission. Initial budget submission = $438,300,000.

j Initial budget submission. Revised submission unspecified.

k Amended budget submission. Original budget submission = $601,200,000.

l Amended budget submission unchanged from original submission.

Table 3–2. Major Budget Category Programmed Funding History (in thousands of dollars)

Budget Category/Fiscal Year	**1979**	**1980**	**1981**	**1982**	**1983**
Aeronautical Research and Technology	264,100	308,300	271,400	264,800	280,000
Research and Technology Base	109,700	120,767	133,847	172,758	198,475
Systems Technology Programs	154,400	187,533	137,533	92,042	81,525
Space Research and Technology	107,300	115,586	110,700	111,000	124,500
Research and Technology Base	86,277	99,816	100,380	104,646	116,304
Systems Technology Programs	12,023	10,770	8,220	3,354	5,196
Standards and Practices *a*	9,000	5,000	2,100	3,000	3,000
Energy Technology Applications	5,000	3,000	1,000	*b*	—

Budget Category/Fiscal Year	**1984**	**1985**	**1986**	**1987**	**1988**
Aeronautical Research and Technology	315,300	342,400	337,257	374,000	332,900
Research and Technology Base	228,450	223,298	228,557	271,111	257,150
Systems Technology Programs	86,850	119,102	108,700	102,889	75,750
Space Research and Technology	137,000	150,000	151,400	206,000	221,300
Research and Technology Base	124,885	136,358	124,200	130,646	107,146
Systems Technology Programs/ Civil Space Technology Initiative	7,515	8,742	27,200	75,354	114,154 *c*
Standards and Practices	4,600	4,900	— *d*	—	—
Transatmospheric Research and Technology	—	—	—	45,000	52,500

a Formerly called Low Cost Systems Program.

b Program terminated.

c Systems Technology Programs terminated, and Civil Space Technology Initiative begun.

d No programmed amount.

Table 3–3. Total Aeronautical Research and Technology Program Funding (in thousands of dollars)

Year	Request	Authorization	Appropriation	Programmed (Actual)
1979	264,100	275,100	*a*	264,100
1980	308,000 *b*	309,300	*c*	308,300
1981	275,300 *d*	290,800 *e*	276,150 *f*	271,400
1982	264,800 *g*	284,800 *h*	264,800	264,800
1983	280,000 *i*	280,000 *j*	280,000	280,000
1984	302,300 *k*	320,300	302,300	315,300
1985	342,400	352,400	342,400	342,400
1986	354,000	354,000	354,000	337,257
1987	376,000 *l*	376,000	376,000	374,000
1988	375,000	387,000	377,000	332,900

a Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

b Amended budget submission. Original budget submission = $300,300,000. The increase resulted from congressional actions that provided additional appropriations of $5,000,000 for advanced rotorcraft technology and $3,000,000 for variable cycle technology.

c Undistributed. Total 1980 R&D appropriation = $3,838,500,000.

d Amended budget submission. Original budget submission = $290,300,000.

e The Senate authorization committee added $20,500,00 to be distributed as follows: Variable Cycle Engine High Temperature Validation—$4,500,000, High Performance Flight Experiment—$5,500,000, High Speed Structures—$4,000,000, Alternative Fuels Utilization—$4,000,000, Alternative Alloys Studies—$1,000,000, and General Aviation Propeller—$1,500,000. Conference committee authorization of $10,500,000 to have $290,800,000 total.

f Reflects effect of General Provision Section 412. Appended to appropriation on December 15, 1980.

g Amended budget submission. Original budget submission = $323,600,000.

h The House authorization committee increased the amount submitted by NASA to be allocated as follows: $3,000,000 for alternative fuels and materials, $8,000,000 for high-speed systems technology, $4,000,000 for large composite structures, $4,000,000 for high-temperature engine core, $12,000,000 for propfan, and a general reduction of $19,800,000 for a total of $272,000,000 (May 8, 1981). Further debate resulted in a House Authorization Bill for $264,000,000 (June 23, 1981), with specific reductions from earlier amounts not specified). The Senate authorization committee added $51,200,000 for various systems technology programs, amounting to a Senate authorization of $316,000,000.

i Revised budget submission. Initial budget submission = $232,000,000.

j Increase applied to the Systems Technology Program.

k Amended budget submission. Original budget submission = $300,300,000.

l Amended budget submission unchanged from original submission.

Table 3–4. Aeronautics Research and Technology Base Funding History (in thousands of dollars)

Year	**Request**	**Authorization**	**Appropriation**	**Programmed (Actual)**
1979	109,200	[a]	[b]	109,700
1980	119,000 [c]	117,500	[d]	120,767
1981	134,100 [e]	131,100	[f]	133,847
1982	162,500 [g]	[h]	157,800	172,758
1983	182,000	182,000 [i]	182,000	198,475
1984	215,800 [j]	205,100 [k]	217,800 [l]	228,450
1985	233,300	233,300	223,300	223,298
1986	239,300	239,300	239,000	228,557
1987	272,900	272,900 [m]	272,900	271,111
1988	285,200	297,200 [n]	287,200	257,150

[a] Undistributed. Total 1979 Aeronautical Research and Technology Program authorization = $275,100,000.

[b] Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

[c] Amended budget submission. Original budget submission = $117,500,000. Congressional actions resulted in a transfer of $1,500,000 from the Systems Technology Program to the Research and Technology Base Program.

[d] Undistributed. Total 1980 R&D appropriation = $3,838,500,000.

[e] Amended budget submission. Original budget submission = $131,100,000.

[f] Undistributed. Total 1981 Aeronautical Research and Technology Program appropriation = $276,150,000.

[g] Amended budget submission. Original budget submission = $160,800,000.

[h] Undistributed. However, both the House and Senate authorization committees authorized the identical amount of $157,800,000.

[i] The House authorization committee added $6,000,000, but the amount was deleted in the conference committee.

[j] Amended budget submission. Original budget submission = $227,800,000.

[k] Reduction to offset increases in Systems Technology Program authorization (see Table 3–20).

[l] Reduction to offset increases in Systems Technology Program appropriation (see Table 3–20).

[m] The Senate authorization committee authorized allocation of funds as follows: Fluid and Thermal Physics Research and Technology—$49,500,000, Applied Aerodynamics Research and Technology—$57,100,000, Propulsion and Power Research and Technology—$35,700,000, Materials and Structures Research and Technology—$39,000,000, Information Sciences Research and Technology—$26,800,000, Controls and Guidance Research and Technology—$24,500,000, Human Factors Research and Technology—$24,000,000, Flight Systems Research and Technology—$21,500,000, and Systems Analysis—$4,800,000.

[n] The Senate authorization committee authorized allocation of funds as follows: Fluid and Thermal Physics Research and Technology—$29,000,000, Applied Aerodynamics Research and Technology—$61,000,000, Propulsion and Power Research and Technology—$41,000,000, Materials and Structures Research and Technology—$42,000,000, Information Sciences Research and Technology—$26,000,000, Controls and Guidance Research and Technology—$27,600,000, Human Factors Research and Technology—$26,000,000, Flight Systems Research and Technology—$26,100,000, and Systems Analysis—$6,500,000 for a total of $285,200.000. The conference committee increased authorization to $297,200,000, with the increase unspecified by category.

Table 3–5. Aerodynamics (Fluid and Thermal Physics) Research and Technology Funding History (in thousands of dollars) [a]

Year (Fiscal)	Submission	Programmed (Actual)
1979	16,500	18,500
1980	22,240	22,587
1981	23,200	23,800
1982	37,100	38,505
1983	43,100	42,665
1984	44,700	43,404
1985	44,000	28,498
1986	30,400	29,210
1987	39,500	39,141
1988	24,600	23,718

[a] Redesignated Fluid and Thermal Physics Research and Technology with FY 1981 revised budget estimate.

Table 3–6. Propulsion (and Power) Systems Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	20,900 [a]	25,500
1980	26,900	26,436
1981	32,400	31,800
1982	37,100	18,616 [b]
1983	16,600	16,600
1984	20,000	23,500
1985	28,700	33,636
1986	33,800	32,355
1987	38,700	41,365
1988	45,800	46,662

[a] Combined Propulsion Environmental Impact Minimization Research and Technology and Propulsion Components Research and Technology budget categories.

[b] Proportion of Propulsion Systems Research and Technology transferred to Fluid and Thermal Physics Research and Technology budget category (see Table 3–5).

Table 3–7. Materials and Structures (Aeronautics) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	17,900 *a*	15,200
1980	16,100	16,077
1981	19,300	17,800
1982	22,100	21,548
1983	24,700	23,200
1984	23,200	23,900
1985	27,800	27,800
1986	29,500	27,830
1987	39,000	35,536
1988	37,200	28,453

a Combined Materials Research and Technology and Structures Research and Technology budget categories.

Table 3–8. General Aviation Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	— *a*	6,800
1980	7,000	7,009
1981	7,500	6,600
1982	7,700	— *b*

a No equivalent budget category.

b Budget category eliminated.

Table 3–9. Applied Aerodynamics Research and Technology Funding History (in thousands of dollars) a

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1984	— *b*	42,300
1985	42,000	50,900
1986	55,300	51,680
1987	56,100	55,885
1988	52,800	56,868

a Includes programs for high-performance aircraft research and technology, powered-lift research and technology, flight dynamics, supersonic aircraft integration technology, rotorcraft research and technology, laminar flow control research, and subsonic configuration/propulsion/airframe integration.

b No budget category.

Table 3–10. Low Speed (Subsonic) Aircraft Research and Technology Funding History (in thousands of dollars) a

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	13,000	11,100
1980	11,200	13,884
1981	11,700	9,600
1982	11,300	13,538
1983	7,500 *b*	9,000
1984	18,900 *c*	— *d*

a Category includes rotorcraft through FY 1982.

b Reduction in amount from previous year reflected reduced activity in materials and structures and aerodynamics systems research.

c Increase over previous year reflected redirected funding from other ongoing research and technology base programs to support research in laminar flow control and advanced transport operations systems. Also supported general aviation aerodynamics and flight dynamics efforts.

d Incorporated into Applied Aerodynamics Research and Technology (see Table 3–9).

Table 3–11. High Speed (High-Performance) Aircraft Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	13,900	14,000
1980	14,800	13,846
1981	16,500	20,600
1982	26,000	29,029
1983	38,000	39,240
1984	37,000	— *a*

a Incorporated into Applied Aerodynamics Research and Technology (see Table 3–9).

Table 3–12. Rotorcraft Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1982	—	20,175 *a*
1983	23,000	23,000
1984	23,000	— *b*

a First time budget category used in NASA Budget Estimate.

b Incorporated into Applied Aerodynamics Research and Technology (see Table 3–9).

Table 3–13. Avionics and Flight Control (Aircraft Controls and Guidance) Research and Technology Funding History (in thousands of dollars) [a]

Year (Fiscal)	Submission	Programmed (Actual)
1979	5,200	4,000
1980	4,800	4,804
1981	5,400	5,400
1982	7,000	7,119
1983	11,900	11,900
1984	12,200	19,602
1985	20,500	20,600
1986	22,100	20,653
1987	24,100	22,789
1988	21,200	20,905

[a] Renamed Aircraft Controls and Guidance with FY 1982 revised budget estimate.

Table 3–14. Human Factors Research and Technology Funding History (in thousands of dollars) [a]

Year (Fiscal)	Submission	Programmed (Actual)
1979	5,600	5,000
1980	5,700	5,872
1981	6,500	6,147
1982	8,000	8,218
1983	10,200	10,070
1984	10,500	19,934
1985	20,300	20,300
1986	22,000	21,360
1987	24,000	23,954
1988	20,600	20,495

[a] Formerly called Human-Vehicle Research and Technology.

Table 3–15. Multidisciplinary Research and Technology Funding History (in thousands of dollars) [a]

Year (Fiscal)	Submission	Programmed (Actual)
1979	— [a]	3,600
1980	3,760	3,760
1981	4,700	5,000
1982	6,000	7,500
1983	3,500	3,600
1984	3,700	— [b]

[a] No equivalent budget category.

[b] Budget category eliminated.

Table 3–16. Transport Aircraft Research and Technology Funding History (in thousands of dollars) *a*

Year (Fiscal)	Submission	Programmed (Actual)
1979	5,500	6,000
1980	6,500	6,492
1981	7,100	7,100
1982	8,100	— *b*

a Formerly called Aircraft Operations and Aviation Safety Research and Technology.

b No budget category in NASA Budget Estimate.

Table 3–17. Computer Science and Applications (Information Science) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1982	—	8,510 *a*
1983	19,200	19,200
1984	22,300	34,943 *b*
1985	21,100	21,100
1986	24,900	23,816
1987	23,800	23,800
1988	19,000	19,189

a First time budget category used in NASA Budget Estimate.

b Renamed Information Sciences Research and Technology.

Table 3–18. Flight Systems Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1984	—	17,504 *a*
1985	16,300	17,864
1986	18,300	17,891
1987	21,900	23,134
1988	24,800	25,400

a First time budget category used in NASA Budget Estimate.

Table 3–19. System Studies Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Authorization**	**Appropriation**	**Programmed (Actual)**
1979	3,000	— *a*	— *b*	— *c*
1980	3,200	3,200	— *d*	— *e*

a Undistributed. Total 1979 Aeronautical Research and Technology Program authorization = $275,100,000.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c Incorporated in Aeronautical System Studies Technology Programs budget category (see Table 3–29).

d Undistributed. Total 1980 R&D appropriation = $3,838,500,000.

e No budget category in NASA Budget Estimate. See Aeronautical System Studies Technology Programs (Table 3–29).

Table 3–20. Systems Technology Program Funding History (in thousands of dollars)

Year (Fiscal)	**Request**	**Authorization**	**Appropriation**	**Programmed (Actual)**
1979	85,645	— *a*	— *b*	154,400
1980	106,100 *c*	115,100 *d*	— *e*	187,533
1981	141,850 *f*	159,700	— *g*	137,553
1982	70,500 *h*	— *i*	107,000	92,042
1983	82,300 *j*	98,000 *k*	98,000	81,525
1984	86,500 *l*	115,200 *m*	84,500 *n*	86,850
1985	119,100 *o*	119,100 *p*	119,100	119,102
1986	113,700 *q*	114,700 *r*	114,700	108,700
1987	103,100	103,100 *s*	103,000	102,889
1988	83,200 *t*	89,800 *u*	89,800	75,750

a Undistributed. Total 1979 Aeronautical Research and Technology Program authorization = $275,100,000.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c NASA Budget Estimate as published by the NASA Comptroller's Office does not break out Experimental Programs and System Studies as appearing in chronological history of congressional action. Total 1980 submission according to Comptroller's Office = $189,900,000.

d Increase over NASA submission of $9,000,000 for Variable-Cycle Engine Technology ($4,000,000) and Advanced Rotorcraft Technology ($5,000,000).

e Undistributed. Total 1980 R&D appropriation = $3,838,500,000. Notes indicate that $4,000,000 was to be allocated for Variable-Cycle Engine Technology and $5,000,000 for Advanced Rotorcraft Technology.

f Amended budget submission. Original budget submission = $159,200,000.

g Reflected recission.

h Amended budget submission. Original budget submission = $162,800,000. Deemphasis on Systems Technology reflects the objective of reducing the federal role in areas that directly support industry for product development, while retaining those efforts related to longer range technology and to defense considerations.

i Undistributed. Total 1982 Aeronautical Research and Technology Program authorization = $284,800,000.

j Increase was attributable to a congressional increase that provided continuing support for selected ongoing programs in the advanced propulsion, subsonic aircraft, and rotorcraft systems technology areas.

k The House authorization committee increased amount to $79,100,000 to be applied as follows: Energy Efficient Transport—$1,100,000, Advanced Turboprops—$9,800,000, Energy

Table 3–20 continued

Efficient Engine—$7,000,000, Terminal Configured Vehicle—$5,000,000, Turbine Engine Hot Section Technology—$4,700,000, Advanced Rotorcraft Technology and Helicopter Transmission Research—$4,500,000, Broad Property Fuels Technology—$4,200,000, Powered Lift and Tilt Rotor Technology—$3,800,000, and Research and Technology Base—$6,000,000. To partially offset the additions, the committee reduced the amounts for activities that were primarily directed at military application: Low Speed Systems Technology and High Speed Systems Technology ($13,000,000). The Senate authorization committee eliminated additional amount for Research and Technology Base but allocated additional funds to Systems Technology as follows: Aeronautical Systems Studies—$2,000,000, Turbine Engine Hot Section—$2,500,000, Broad Property Fuels—$3,000,000, Helicopter Transmission—$1,500,000, Critical Aircraft Resources—$2,200,000, General and Commuter Aviation—$3,000,000, Composite Primary Aircraft Structure—$6,000,000, Energy Efficient Transport—$1,100,000, Terminal Configured Vehicle—$4,600,000, Laminar Flow Control—$3,000,000), Energy Efficient Engine—$7,500,000), and Advanced Turboprop—$27,600,000 for a total of $114,000,000. The conference committee reallocated the authorized funds so that the amounts added to the NASA request went to acceleration of advanced turboprop ($15,000,000), composite primary aircraft structures ($6,000,000), general and commuter aviation including small engine component technology ($3,000,000), broad property fuels ($3,000,000), energy efficient engine ($7,000,000), energy efficient transport ($3,000,000), and terminal configured vehicle ($5,000,000). The remaining $6,000,000 was to be applied to those projects that NASA considered most feasible.

l Revised budget submission. Original budget submission = $72,000,000.

m The House appropriations committee added $20,000,000 for Advanced Turboprop and $14,000,000 for Advanced Transport Operating System (ATOPS). The Senate authorization committee increased the amount for ATOPS to fund a total of $22,700,000 for Systems Technology. Advanced Turboprop remained at $20,000,000.

n The House authorization committee added $20,000,000 for Advanced Turboprop (taking $10,000,000 from Research and Technology Base) and reduced the amount for Numerical Aerodynamic Simulation by $5,000,000 and the amount for ATOPS by $5,000,000. The Senate appropriations committee reduced the amount for Numerical Aerodynamic Simulation by $3,000,000 and added $10,000,000 to Advanced Propulsion and Composite Materials. The appropriations conference committee reduced the amount for Numerical Aerodynamic Simulation by $3,000,000 and added $15,000,000 to Advanced Turboprop, Composite Materials, and Laminar Flow.

o Revised budget submission. Original budget submission = $109,100,000.

p The Senate authorization committee authorized allocation of Systems Technology Program funds as follows: Rotorcraft Systems Technology—$26,600,000, High-Performance Aircraft Systems Technology—$21,000,000, Subsonic Aircraft Systems Technology—$19,000,000, Advanced Propulsion Systems Technology—$31,100,000, and Numerical Aerodynamic Simulation—$26,500,000 for a total of $124,100,000. The conference committee returned to the $19,100,000 amount. Of the total authorization, $24,000,000 was authorized only for activities that were designed to lead to a flight test of a single rotation or counter-rotation turboprop concept no later than 1987 (and for supporting research and technology).

q Revised budget submission. Original budget submission = $114,700,000.

r The Senate authorization committee authorized allocation of Systems Technology Program funds as follows: Rotorcraft Systems Technology—$20,500,000, High-Performance Aircraft Systems Technology—$21,800,000, Subsonic Aircraft Systems Technology—$0 (to be terminated at the end of 1985), Advanced Propulsion Systems Technology—$44,200,000, and Numerical Aerodynamic Simulation—$28,200,000.

s The authorization committee allocated funds as follows: Rotorcraft Systems Technology—$18,700,000, High-Performance Aircraft Systems Technology—$26,000,000, Advanced Propulsion Systems Technology—$28,400,000, and Numerical Aerodynamic Simulation—$30,000,000.

t Revised budget submission. Original budget submission = $3,200,000.

u The Senate authorization committee allocated funds as follows: Rotorcraft Systems Technology—$5,000,000, High-Performance Aircraft Systems Technology—$14,000,000, Advanced Propulsion Systems Technology—$30,500,000, and Numerical Aerodynamic Simulation—$39,700,000.

Table 3–21. Aircraft Energy Efficiency Funding History (in thousands of dollars) a

	1979	1980	1981	1982	1983	1984	1985	Total *b*
Engine Component Improvement	12.9	6.1	—	—	—	—	—	39.5
Energy Efficient Engine	43.2	55.6	48.7	22.9	—	—	—	198.0
Energy Efficient Transport	13.9	25.4	15.3	9.1	—	—	—	85.0
Composite Primary Aircraft Structures	20.5	15.9	6.4	22.9	—	—	—	94.3
Laminar Flow Control	3.7	10.3	11.6	4.5	—	—	—	37.2
Advanced Turboprops Phase I	3.2	2.8	—	—	—	—	—	8.0
Advanced Turboprops Phase II	—	—	3.0	6.0	8.0	9.0	6.0	32.0
Total (NASA Share)	**97.4**	**116.1**	**85.0**	**46.7**	**9.6**	**9.0**	**6.0**	**494.0**
Industry Share	(7.9)	(10.6)	(7.2)	(2.6)	(—)	(—)	(—)	(37.2)

a Aircraft Energy Efficiency appeared as a supplement in the 1980 Budget Estimate only (although some of the subcategories appeared at other times). It combined particular subcategories to form a new initiative. The Aircraft Energy Efficiency budget categories were subcategories to the Transport Aircraft Systems Technology and Advanced Propulsion Systems budget categories. Presumably, the FY 1979 figures are actuals, and the FY 1980 and future figures are estimates.

b Includes funding prior to FY 1979.

Table 3–22. Materials and Structures Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	4,500	3,300
1980	5,555	5,553
1981	9,600	8,715
1982	6,600	1,600
1983	— *a*	—
1987 *b*	—	(7,200) *c*
1988	8,800	8,818

a The integrated program for aerospace vehicle design continued under Computer Science and Applications Research and Technology budget category. Other activities concluded in FY 1982.

b No Materials and Structures Systems Technology budget category from FY 1983 to FY 1987.

c Budget category reinstated. The Advanced High-Temperature Engine Materials Technology Program was transferred from the Advanced Propulsion Systems Technology Program to Materials and Structures Systems Technology.

Table 3–23. Low Speed (Subsonic) Aircraft Systems Technology Funding History (in thousands of dollars) [a]

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	14,545 [b]	14,970
1980	23,250	23,175
1981	24,300	23,511
1982	25,600	27,022
1983	17,000	16,975
1984	5,000 [c]	5,000
1985	19,000	19,000

[a] Category includes rotorcraft through FY 1982.

[b] Combined Aircraft Operating Systems Technology and Rotorcraft Systems Technology budget categories.

[c] Reduced request because of the completion of several activities.

Table 3–24. High Speed (High-Performance) Aircraft Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	11,060	9,800
1980	14,800	14,695
1981	16,700	16,615
1982	7,700	13,800
1983	15,000	14,950
1984	19,900	19,900
1985	21,500	21,530
1986	20,800	17,800
1987	26,000	25,985
1988	12,800	5,430

Table 3–25. Propulsion Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	28,400 [a]	3,600
1980	6,700	6,700
1981	4,900	4,400
1982	500	500
1983	— [b]	—

[a] The large difference between submission and programmed amounts reflected new Advanced Propulsion Systems budget category and the relocation of some other propulsion systems functions in other budget categories.

[b] Technology efforts continued under the Propulsion Systems Research and Technology Program.

Table 3–26. Avionics and Flight Control Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	2,400	3,000
1980	2,850	1,206
1981	1,200	1,200
1982	1,300	1,300
1983	— *a*	—

a Activities were transferred to Aircraft Controls and Guidance Research and Technology budget category.

Table 3–27. Transport Aircraft Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	19,140 *a*	44,750
1980	58,545	57,891
1981	33,100	32,746
1982	13,400	— *b*

a Incorporated Advanced Civil Aircraft Systems Technology and Aerodynamic Vehicle Systems Technology activities. No equivalent budget category.

b Activities transferred to Subsonic Aircraft budget category.

Table 3–28. Advanced Propulsion Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	— *a*	66,255
1980	72,500	72,278
1981	47,800 *b*	46,196
1982	15,400 *c*	26,155
1983	28,000	27,300
1984	17,000	17,000
1985	26,100 *d*	26,100
1986	44,200	42,200
1987	28,400	28,220
1988	18,000 *e*	17,955

a No submission in this category.

b Significant drop from prior year because of the completion of several activities.

c Reduction in submission reflects the descoping of the energy efficient engine program and the advanced turboprop effort, as well as the completion of other activities.

d Increase reflected realignment of $10,000,000 to the advanced turboprop program from the research and technology base program for efforts leading to an initial flight test in 1987, as directed by Congress.

e Reflected the transfer of the advanced high-temperature engine materials technology program to Materials and Structures Systems Technology (see Table 3–22).

Table 3–29. Aeronautical System Studies Technology Funding History (in thousands of dollars) [a]

Year (Fiscal)	Submission	Programmed (Actual)
1979	— [b]	4,825
1980	4,100	4,134
1981	3,200	3,125
1982	— [c]	—

[a] Formerly System Studies (see Table 3–19).

[b] See Table 3–19.

[c] Program terminated.

Table 3–30. Numerical Aerodynamic Simulation Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1984	17,000	17,000
1985	26,500	26,472
1986	28,200	28,200
1987	30,000	29,984
1988	39,000	39,018

Table 3–31. Advanced Rotorcraft Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1982	— [a]	21,665
1983	22,300	22,300
1984	27,600	27,950
1985	26,000	26,000
1986	20,500	20,500
1987	18,700	18,700
1988	4,600 [b]	4,529

[a] No budget category.

[b] Reduction reflected the elimination of funding for the Technology-for-Next-Generation Rotorcraft Program.

Table 3–32. Experimental Programs Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	66,255	— *a*	— *b*	— *c*
1980	73,500	73,500	— *d*	— *e*

a Undistributed. Total 1979 Aeronautical Research and Technology Program authorization = $275,100,000.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c No budget category in NASA Budget Estimate.

d Undistributed. Total 1980 R&D appropriation = $3,838,500,000.

e No budget category in NASA Budget Estimate.

Table 3–33. Space Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	107,300 *a*	111,300	— *b*	107,300
1980	115,800 *c*	119,400	— *d*	115,586
1981	110,200 *e*	115,200	110,700 *f*	110,700
1982	125,300 *g*	129,300	111,000	111,000
1983	123,000	128,000	123,000	124,500
1984	137,000 *h*	143,000	138,000	137,000
1985	150,000	150,000	154,000	150,000
1986	168,000	166,000	168,000	151,400
1987	171,000 *i*	183,200	185,200 *j*	206,000
1988	250,000 *k*	234,000	235,000	221,300

a Amended budget submission. Original budget submission = $108,300,000.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c Amended budget submission. Original budget submission = $116,400,000.

d Undistributed. Total 1980 R&D appropriation = $3,838,500,000.

e Amended budget submission. Original budget submission = $115,200,000.

f Reflected recission. Unchanged from earlier appropriated amount that reflected the effect of General Provision Sec. 412 appended to appropriation on December 15, 1980.

g Amended budget submission. Original budget submission = $141,000,000.

h Amended budget submission. Original budget submission = $138,000,000.

i Amended budget submission. Original budget submission = $180,200,000.

j Additional amount was the result of congressional action.

k Amended budget submission unchanged from original submission.

Table 3–34. Space Research and Technology Base Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	71,795 *a*	71,700	— *b*	86,277
1980	99,785 *c*	77,100	— *d*	99,816
1981	100,300 *e*	105,300 *f*	101,100 *g*	100,380
1982	115,300 *h*	117,300 *i*	— *j*	104,646
1983	115,100 *k*	120,600 *l*	115,600	116,304
1984	125,400 *m*	131,300 *n*	126,200	124,885
1985	150,000 *o*	136,000	140,000	136,358
1986	132,800 *p*	140,000	140,000	124,200
1987	133,600	133,600 *q*	133,600	130,646
1988	115,900	115,900 *r*	115,900	107,146

a Amended budget submission. Original budget submission = $71,700,000.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c Amount in *1980 Chronological History* = $77,100,000. The amount in the table (as published in the NASA Budget Estimate) reflects different split between the Research and Technology Base and Systems Technology Programs, with $99,785,000 allocated for Research and Technology Base and $11,015,000 allocated for Systems Technology. The amount agrees with the sum of amounts for individual programs/budget categories. (The *Chronological Budget History* does not provide amounts for individual programs.)

d Undistributed. Total 1980 R&D appropriation = $3,838,500,000.

e Amended budget submission. Original budget submission = $103,400,000.

f Amended budget increased $3,000,000 to enhance advanced chemical propulsion technology activities and to accelerate expander cycle dual-thrust engine technology, as well as $2,000,000 for enhancements of space platform and large space structures advanced technology activities.

g Reflected recission. Unchanged from earlier appropriated amount that reflected the effect of General Provision Sec. 412 appended to appropriation on December 15, 1980.

h Amended budget submission. Original budget submission = $124,800,000.

i House action increased authorization $2,000,000 for chemical propulsion technology. The Senate restored $5,000,000, which included an additional amount of $200,000 for space power and electric propulsion.

j Undistributed. Total 1982 Space Research and Technology appropriation = $111,000,000.

k Amended budget submission. Original budget submission = $115,600,000.

l A total of $5,000,000 was added for propulsion research and technology activities.

m Revised budget submission. Original budget submission = $126,200,000.

n The House authorization committee added $5,000,000 for university research instrumentation and lab equipment ($2,500,000) and to augment advanced chemical propulsion technology ($2,500,000).

o Amended budget submission. Original budget submission = $136,000,000.

p Revised budget submission. Original budget submission = $140,000,000.

q The Senate authorization committee authorized the allocation of funds as follows: Aerothermodynamics Research and Technology—$11,200,000, Space Energy Conversion Research and Technology—$20,400,000, Propulsion Research and Technology—$21,000,000, Materials and Structures Research and Technology—$18,900,000, Space Data and Communications Research and Technology—$13,600,000, Information Sciences Research and Technology—$10,200,000, Controls and Guidance Research and Technology—$7,500,000, Human Factors Research and Technology—$2,300,000, Space Flight Research and Technology—$22,400,000, and Systems Analysis—$6,100,000.

Table 3–34 continued

r The Senate authorization committee authorized the allocation of funds as follows: Aerothermodynamics Research and Technology—$11,100,000, Space Energy Conversion Research and Technology—$14,600,000, Propulsion Research and Technology—$14,500,000, Materials and Structures Research and Technology—$17,900,000, Space Data and Communications Research and Technology—$8,900,000, Information Sciences Research and Technology—$8,000,000, Controls and Guidance Research and Technology—$6,300,000, Human Factors Research and Technology—$4,900,000, Space Flight Research and Technology—$23,200,000, and Systems Analysis—$6,500,000.

Table 3–35. Materials and Structures (Space) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	14,700 *a*	16,400
1980	16,400	25,376
1981	14,000	14,000
1982	14,100	14,565
1983	14,700	13,245
1984	13,900	16,694
1985	18,800	18,800
1986	18,600	18,126
1987	18,900	20,877
1988	15,900	17,215

a Combined Materials Research and Technology and Structures Research and Technology budget categories.

Table 3–36. Space Power and Electric Propulsion (Space Energy Conversion) Research and Technology Funding History (in thousands of dollars) a

Year (Fiscal)	Submission	Programmed (Actual)
1979	9,200 *b*	17,000
1980	19,750	19,364
1981	19,200	18,900
1982	18,500	18,080 *c*
1983	17,400	17,900
1984	22,100	22,006
1985	22,500	22,312
1986	21,200	19,955
1987	20,400	20,922
1988	12,500	12,154

a Renamed Space Energy Conversion Research and Technology with FY 1983 revised estimate.

b Included only Electric Propulsion activities.

c Renamed Space Energy Conversion Research and Technology with Revised FY 1983 Budget Estimate.

Table 3–37. Platform Systems (Systems Analysis) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1982	—	2,649 *a*
1983	5,100	6,020
1984	8,800	7,200 *b*
1985	6,610	6,788
1986	6,800	6,438
1987	6,100	6,576
1988	5,700	5,376

a Funded primarily from Spacecraft Systems budget category. Included systems analysis, operations technology, and crew and life support technology.

b Descoped to include only Systems Analysis.

Table 3–38. Information Systems (Space Data and Communications) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	— *a*	16,308
1980	20,600	21,847
1981	21,300	21,100
1982	22,900	16,902 *b*
1983	18,100	16,609
1984	17,800	17,802
1985	16,500	16,500
1986	16,000	15,384
1987	13,600	13,252
1988	7,900	7,765

a No equivalent category.

b Most funding was used for the new Space Data and Communications budget category.

Table 3–39. Computer Sciences and Electronics (Information Sciences) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1982	— *a*	14,130
1983	15,700	16,165
1984	16,100	16,001 *b*
1985	17,600	17,590
1986	9,900 *c*	12,462
1987	10,200	8,827
1988	7,700	7,428

a No budget category.

b Renamed Information Sciences Research and Technology.

c Reduction from prior year because of the transfer of Automation Robotics funding to Systems Technology and a $300,000 reduction in Information Sciences to support Transatmospheric Technology efforts.

Table 3–40. Electronics and Automation Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	— *a*	8,200
1980	8,550	8,123
1981	7,900	7,700
1982	8,100	— *b*

a No budget category.

b Activities moved to Computer Sciences and Electronics budget category.

Table 3–41. Transportation Systems (Space Flight) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	—	7,074
1980	10,235	10,725
1981	12,400	8,900
1982	8,200	7,073
1983	7,800	7,300
1984	7,400	6,800 *a*
1985	11,450	11,468
1986	17,000 *b*	14,054
1987	22,200	20,096
1988	21,400	21,052

a Renamed Space Flight Systems.

b Increase included the consolidation of funds from other Research and Technology Base programs for Control of Flexible Structures, Transatmospheric Technology, Aerospace Industry/University Space Flight Experiments, and Cryogenic Fluid Management Technology Activities. In addition, the aero-assist portion of the Orbital Transfer Vehicle systems technology program was transferred to this Research and Technology Base program from Systems Technology.

Table 3–42. (Chemical) Propulsion Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	9,200	8,600
1980	8,900	8,900
1981	12,400	12,400
1982	13,700	12,956
1983	15,400	16,600
1984	16,400	19,497
1985	20,500	20,500
1986	22,300	18,156
1987	21,000	18,844
1988	13,300	12,679

Table 3–43. Spacecraft Systems Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	— *a*	5,495
1980	7,250	7,437
1981	9,000	8,900
1982	9,100	5,071
1983	3,500	4,520
1984	5,200	— *b*

a No budget category.

b No budget category.

Table 3–44. Fluid Physics (Aerothermodynamics) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1979	5,800 *a*	5,200
1980	5,400	5,400
1981	7,800	7,800
1982	7,900	7,894
1983	8,500	8,385
1984	8,400	8,480
1985	10,100	10,100
1986	10,800	10,490
1987	11,400	11,678
1988	10,300	10,170

a Formerly called Entry Research and Technology.

Table 3–45. Control and Human Factors (Controls and Guidance) Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Programmed (Actual)**
1982	—	2,964 *a*
1983	6,800	7,460
1984	8,300	7,402 *b*
1985	8,600	8,600
1986	7,500	7,035
1987	7,500	7,300
1988	5,500	5,260

a New budget category funded primarily from Spacecraft Systems.

b Renamed Controls and Guidance Research and Technology. Human Factors became a separate budget category.

Table 3–46. Human Factors Research and Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1984	—	3,003
1985	3,700	3,700
1986	2,300	2,100
1987	2,300	2,274
1988	4,200	4,047

Table 3–47. System Studies (Space) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	2,000	— *a*	— *b*	— *c*
1980	2,200	2,200	— *d*	— *e*

a Undistributed. Total 1979 Space Research and Technology authorization = $111,300,000.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c No budget category in NASA Budget Estimate.

d Undistributed. Total 1980 R&D appropriation = $3,383,500,000.

e No budget category in NASA Budget Estimate.

Table 3–48. Systems Technology Program (Civil Space Technology Initiative) Funding History (in thousands of dollars) [a]

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	7,900 *b*	10,900	— *c*	12,023
1980	11,015	19,000 *d*	— *e*	10,770
1981	7,800 *f*	7,800	7,500 *g*	8,220
1982	2,800 *h*	9,000 *i*	— *j*	3,354
1983	4,900 *k*	4,400	3,000	5,196
1984	7,000 *l*	7,200	7,200	7,515
1985	8,750 *m*	9,100	9,100	8,742
1986	27,200 *n*	20,000	20,000	27,200
1987	37,400	37,400 *o*	37,400	75,354
1988	115,200 *p*	118,100 *q*	119,100	114,154

a Designated as Civil Space Technology Initiative (CSTI) program starting with the FY 1988 budget submission.

b The Systems Technology Program budget categories provided at the time of the FY 1979 budget requests as listed in the NASA Budget Estimate were not equivalent to the categories provided for the programmed amounts as listed in the FY 1981 NASA Budget Estimate.

c Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

d The Senate authorization committee increased the amount $3,000,000 for Large Space Structures.

e Undistributed. Total 1980 R&D appropriation = $9,700,000.

f Amended budget submission. Original budget submission = $103,400,000.

g Reflected recission. Unchanged from earlier appropriated amount that reflected the effect of General Provision Sec. 412 appended to appropriation on December 15, 1980.

h Amended budget submission. Original budget submission = $13,200,000. Reflects intention to eliminate the Systems Technology Program.

i The House authorization committee increased Information Systems Technology by $2,000,000.

j Undistributed. Total 1982 Space Research and Technology appropriation = $111,000,000.

k Revised budget submission. Initial budget submission = $4,400,000. No budget categories from prior years were included.

l Revised budget submission. Initial budget submission = $7,200,000.

m Revised budget submission. Initial budget submission = $9,100,000.

n Revised budget submission. Original budget submission = $27,200,000.

o The Senate authorization committee authorized the allocation of funds as follows: Chemical Propulsion Systems Technology—$8,100,000, Control of Flexible Structures Flight Experiment—$11,300,000, and Automation and Robotics Technology—$18,000,000.

p Space Systems Technology programs were incorporated into the CSTI program in FY 1988.

q The Senate authorization committee authorized the allocation of funds as follows: Propulsion—$1,200,000, Vehicle—$15,000,000, Propulsion Research and Technology—$21,000,000, Materials and Structures Research and Technology—$18,900,000, Information—$17,400,000, Large Structures and Control—$22,800,000, Power—$14,000,000, and Automation and Robotics—$96,100,000. The conference committee increased the total amount.

Table 3–49. Space Systems Studies Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	— *a*	2,000
1980	2,200	2,323
1981	2,000	2,083
1982	— *b*	—

a No equivalent budget category.

b Amended budget submission. The deletion of the original $500,000 budget request reflected a decision to eliminate Space Systems Studies as an independent line item and to conduct necessary studies within the Research and Technology Base or specific Systems Technology programs as appropriate.

Table 3–50. Information (Systems) Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	— *a*	—
1980	2,600	1,500
1981	4,100	4,026
1982	— *b*	—
1983 *c*	16,500	16,310

a No equivalent budget category.

b Amended budget submission. The deletion of the original $9,400,000 estimate reflected a decision to eliminate this program as an independent line item and to consolidate the remaining elements into the Information Systems program in the Research and Technology Base.

c The budget category was reinstated as part of CSTI.

Table 3–51. Space Flight Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1982	—	3,354 *a*
1983	4,900	5,196
1984	7,000	7,515
1985	6,650	6,642
1986	6,200	11,200 *b*
1987	11,300	11,254

a Included Space Flight Experiments, the Long Duration Exposure Facility, and the Ion Auxiliary Propulsion System.

b Included Control of Flexible Structures funding.

Table 3–52. Spacecraft Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1979	— *a*	10,023
1980	6,215	6,947
1981	1,400 *b*	2,075
1982	2,800	— *c*

a No equivalent budget category.

b Reduction in FY 1981 submission from prior year reflected the completion and delivery of most Spacelab experiments and the development and completion of most Long Duration Exposure Facility experiments during FY 1981, as well as the delivery of flight hardware for the experimental test of the eight-centimeter ion engine auxiliary propulsion system to the U.S. Air Force in FY 1980.

c No budget category.

Table 3–53. Automation and Robotics Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1986	10,200	10,200
1987	18,000	18,000
1988	25,100	25,332

Table 3–54. (Chemical) Propulsion Systems Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1985	2,100	2,100
1986	5,800	5,800
1987	8,100	46,100 *a*
1988	38,800	23,600

a Increase reflected the expansion of research on Earth-to-orbit technology aimed at assuring a mid-1990 capability to enable the development of reusable, high-performance, liquid oxygen/hydrogen, and high-density fuel propulsion systems for next-generation space transportation vehicles beyond the Shuttle. Also reflected a new Booster Technology program.

Table 3–55. Vehicle Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1988	15,000	15,000

Table 3–56. Large Structures and Control Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1988	22,000	22,158

Table 3–57. High-Capacity Power Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed (Actual)
1988	12,800	12,754

Table 3–58. Experimental Programs Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	17,700	17,700	— *a*	— *b*
1980	18,100	18,100	— *c*	— *d*

a Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

b No budget category in NASA Budget Estimate.

c Undistributed. Total 1980 R&D appropriation = $3,383,500,000.

d No budget category in NASA Budget Estimate.

Table 3–59. Standards and Practices Funding History (in thousands of dollars) a

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	9,000	9,000	— *b*	9,000
1980	5,000 *c*	3,000	— *d*	5,000
1981	2,100 *e*	2,100	2,100 *f*	2,100
1982	3,000 *g*	3,000	— *h*	3,000
1983	3,000	3,000	3,000	3,000
1984	4,600	4,600	4,600	4,600
1985	4,900	4,900	4,900	4,900
1986	8,000	8,000	8,000	— *i*
1987	9,200	9,200	9,200	— *j*

a Formerly named Low Cost Systems.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c Amended budget submission. Original budget submission = $3,000,000.

d Undistributed. Total 1980 R&D appropriation = $3,383,500,000.

e Amended budget submission. Original budget submission = $4,000,000.

f Reflected recission. Unchanged from earlier appropriated amount that reflected the effect of General Provision Sec. 412 appended to appropriation on December 15, 1980.

g Amended submission unchanged from original submission.

h Undistributed. Total Space Research and Technology = $111,000,000.

i No programmed amount.

j No programmed amount.

Table 3–60. Energy Technology Applications Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	3,000	5,000	— *a*	5,000
1980	3,000	5,000 *b*	— *c*	3,000
1981	4,000 *d*	4,000	1,900 *e*	1,900
1982	4,400	0 *f*	0	—

a Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

b The Senate authorization committee increased the amount for Energy Technology Verification and Identification by $2,000,000.

c Undistributed. Total 1980 R&D appropriation = $3,383,500,000.

d Amended budget submission unchanged from original submission.

e Reflected recission.

f No authorization or appropriation passed for FY 1982.

Table 3–61. Transatmospheric Research and Technology Funding History (in thousands of dollars) a

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1987	35,000 *b*	40,000	40,000	45,000
1988	52,500 *c*	66,000	53,000 *d*	52,500

a Budget category to fund the development of the technology base for a potential national aerospace plane. The program was initiated in FY 1986, by FY 1986 funding was included in ongoing Research and Technology Base funding ($16,000,000).

b Revised budget submission. Original budget submission = $45,000,000.

c Revised budget submission. Original budget submission = $45,000,000.

d General reduction reduced the appropriation from $66,000,000 to $53,000,000.

Table 3–62. Helicopter and Compound RSRA Configurations

Feature	Helicopter Configuration	Compound Configuration
Gross Weight	9,200 kilograms	13,100 kilograms
Power Plant	Sikorsky S-61 rotor and drive system powered by twin General Electric T58-GE-5/100 gas turbine engines generating 1,044 shaft kilowatts each	Additional General Electric TF34-GE-44A wing and auxiliary thrust jet engines rated at 41,255 newtons thrust each
Horizontal Stabilizer	“T” tail with a 4.1-meter span and 2.4-square-meter area	Additional 6.5-meter span stabilizer and a rudder and associated controls
Wing Span	None	14 meters

Table 3–63. HiMAT Characteristics

First Flight	July 27, 1979	
First Supersonic Flight	May 11, 1982	
Length	7 meters	
Wing Span	4.6 meters	
Height	1.3 meters	
Weight at Launch	1,543 kilograms	
Thrust	22,240 newtons	
Maximum Speed	Mach 1.4	
Engine	General Electric J-85 turbojet	
Composition (% of total structural weight)	Graphite	26
	Fiberglass	3
	Aluminum	26
	Titanium	18
	Steel	9
	Sintered Tungsten	4
	Miscellaneous	14
Prime Contractor	Rockwell International	
Program Responsibility	NASA Dryden Flight Research Center	

Table 3–64. X-29 Characteristics

Length of Aircraft	14.7 meters
Width of Wing	8.3 meters
Height	4.3 meters
Power Plant	One General Electric F404-GE-400 engine producing 71,168 newtons of thrust
Empty Weight	6,170 kilograms
Takeoff Weight	7,983 kilograms
Maximum Operating Altitude	15,240 meters
Maximum Speed	Mach 1.6
Flight Endurance Time	1 hour
External Wing Structure	Composites
Wing Substructure	Aluminum and titanium
Basic Airframe Structure	Aluminum and titanium

Table 3–65. Boeing 737 Transport Systems Research Vehicle Specifications

Model	Boeing 737-130 (aircraft was a 737-100, but given customer designation of 737-130 when modified to NASA specifications) Serial no. 19437 Boeing designation PA-099 (Prototype Boeing 737)
Date of Manufacture	1967
First Flight	April 9, 1967
Description	Twin-jet, short-range transport
Total Flight Hours:	
Upon Arrival at Langley	978
At End of FY 1993	2,936
Engines	Two Pratt & Whitney JT8D-7s
Thrust	62,272 newtons each
Wing Span	28.3 meters
Length	28.65 meters
Wing Area	91 square meters
Tail Height	11.3 meters
Gross Takeoff Weight	44,362 kilograms
Maximum Payload	13,154 kilograms
Cruising Speed	925 kilometers per hour
Range	3,443 kilometers
Service Ceiling	10,668 meters

Source: Lane E. Wallace, *Airborne Trailblazer: Two Decades With NASA Langley's 737 Flying Laboratory* (Washington, DC: NASA SP-4216, 1994), p. 147.

Table 3–66. Experiments of the Orbiter Experiments Program

Experiment Name	**Principal Technologist**	**STS Flights**	**Description**
Aerodynamic Coefficient Identification Package (ACIP) (Figure 3–20)	D.B. Howes, Johnson Space Center	STS-1, STS-6, STS-8	ACIP provided a way to collect aerodynamic data during the launch, entry, and landing phases of the Shuttle flight. It established an extensive aerodynamic database for the verification of and correlation with ground-based data, including assessments of the uncertainties of such data. It also provided flight dynamics data in support of other technology areas, such as aerothermal and structural dynamics. ACIP incorporated three groups of instruments: dual-range linear accelerometers, angular accelerometers, and rate gyros.
Catalytic Surface Effects (CSE) (Figure 3–21)	D. Stewart, Ames Research Center	STS-2, STS-5	CSE determined the effects of thermal protection system coating catalytic efficiency on orbiter flight convective heating and maximum temperature reduction.
Dynamic, Acoustic, and Thermal Environment (DATA) (Figure 3–22)	W. Bangs, Goddard Space Flight Center	STS-2, STS-5	DATE acquired environmental response and input data for predicting environments for future payloads. The environments were neither constant nor consistent throughout the payload bay and were influenced by interactions between cargo elements. The experiment consisted of accelerometers and force gauges, microphones, and thermal sensors that were installed on the payload components and on the carrying structures.

Table 3–66 continued

Experiment Name	Principal Technologist	STS Flights	Description
Induced Environment Contamination Monitor (IECM) (Figure 3–23)	Marshall Space Flight Center	STS-2, STS-4	The IECM measured and recorded concentration levels of gases and particulate contamination emitted by the Shuttle during all phases of the mission to verify that contamination associated with the orbiter would not preclude or seriously interfere with the gathering of data preparing for or during the orbital flight. The IECM was a self-contained aluminum unit and contained ten and support systems mounted on the Development Flight Instrument Unit.
Tile Gap Heating (TGH) Effects (Figure 3–24)	F. Centolanzi, Ames Research Center	STS-2, STS-5	TGH Effects evaluated the thermal response of different tile gaps and provided optimum tile gap designs for the orbiter thermal protection system. The experiment consisted of a removable carrier panel with eleven thermal protection system tiles of baseline material located on the underside of the orbiter fuselage. The gap spacing and depth between tiles were controlled to assure heating rates no higher than baseline, with the primary objective of identifying optimum heating rates. Thermocouples fitted to the tile surfaces and in the gaps measured the temperature during entry.

Table 3–67. Long Duration Exposure Facility (LDEF) Mission Chronology

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

Table 3–68. Long Duration Exposure Facility (LDEF) Characteristics

Launch Date/Range	April 6, 1984/Kennedy Space Center
Date of Reentry	Retrieved January 12, 1990, on STS-32 (*Columbia*)
Launch Vehicle	STS 41-C (*Challenger*)
Customer/Sponsor	NASA/OAST
Responsible (Lead) NASA Center	Langley Research Center
Mission Objectives	Provide a low-cost means of space access to a large experiment group
Instruments and Experiments	***Materials and Structures*** 1. Growth of Crystals From Solution in Low Gravity attempted to grow single crystals of lead sulfide, calcium carbonate, and synthetic metals in low gravity. 2. Atomic Oxygen-Stimulated Outgassing investigated the effect of atomic oxygen impingement on thermal control surfaces in orbit. 3. Interaction of Atomic Oxygen With Solid Surfaces determined the measurable effects of impingement of high fluxes of atomic oxygen on various solid surfaces, investigated the mechanisms of interaction in several materials (some not chemically affected by oxygen), and altered the exposure, angle of incidence, and temperature of the substrates by their position on the spacecraft and experimental design. 4. Mechanical Properties of High-Toughness Graphite-Epoxy Composite Material tested the effect of space exposure on the mechanical properties of a specially toughened graphite-epoxy composite material. 5. Space-Based Radar Phased-Array Antenna evaluated the space effects on candidate polymeric materials for space-based radar phased-array antennas, degradation mechanisms caused by thermal cycling, ultraviolet and charged particle irradiation, applied load and high-voltage plasma interaction. 6. Composite Materials for Large Space Structures evaluated the space effects on physical and chemical properties of laminated continuous-filament composites and composite resin films for large structures and advanced spacecraft. 7. Epoxy Matrix Composites Thermal Expansion and Mechanical Properties detected possible variation in coefficient of thermal expansion of composite samples in space, detected possible change in the mechanical integrity of composite products, and compared the behavior of two epoxy resins commonly used in space structure production. 8. Composite Materials tested different materials to determine actual useful life and integration of histories of thermal and mechanical characteristics into models of composite structures.

Table 3–68 continued

9. Microwelding of Various Metallic Materials Under Ultravacuum examined metal surfaces representative of mechanism-constituent metals for microwelds after space exposure.
10. Graphite-Polymide and Graphite-Epoxy Mechanical Properties accumulated operational data on space exposure of graphite-polymide and graphite-epoxy material.
11. Polymer Matrix Composite Materials investigated the effect of space exposure on the mechanical properties of polymer matrix composite materials.
12. Spacecraft Materials analyzed the materials specimens to understand changes in properties and structures in space, including structural materials, solar power components, thermal control materials, laser communications components, laser mirror coatings, laser-hardened materials, antenna materials, and advanced composites.
13. Balloon Materials Degradation assessed space exposure effects on balloon films, tapes, and lines.
14. Thermal Control Coatings examined the validity of ground simulations of the space environment to study degradation of satellite thermal control coatings.
15. Spacecraft Coatings determined the space effects on new coatings being developed for spacecraft thermal control. Paint, other coatings, and second-surface mirror samples were exposed—some to all mission environments and some to specific ones. Sample spectral reflectance was measured before and after the mission.
16. Thermal Control Surfaces determined the effects of space on new coatings being developed for spacecraft thermal control. Samples were mounted on an indexing wheel, where a reflectometer periodically recorded reflectance values.
17. Ion-Beam-Textured and Coated Surfaces measured launch and space effects on optical properties of ion-beam-textured high-absorptance solar thermal control surfaces, optical and electrical properties of ion-beam-sputtered conductive solar thermal control surfaces, and weight loss of ion-beam-deposited oxide-polymer films.
18. Cascade Variable-Conductance Heat Pipe verified the ability of a variable-conductance heat pipe system to provide precise temperature control of long-life spacecraft without needing a feedback heater or other power source for temperature adjustment, under conditions of widely varying power input and ambient environment.

Table 3–68 continued

19. Low-Temperature Heat Pipe Experiment Package evaluated the performance in space of a fixed-conductance transporter heat pipe, a thermal diode heat pipe, and a low-temperature phase-change material.
20. Transverse Flat-Plate Heat Pipe evaluated the zero-gravity performances of a transverse flat-plate heat pipe, including heat transport capability, temperature drop, and ability to maintain temperature over varying duty cycles and environments.
21. Thermal Measurements System measured the average LDEF flight temperature and temperature time history of selected components and representative experiment boundary conditions.

Power and Propulsion

22. Space Plasma High-Voltage Drainage determined the long-term current drainage properties of dielectric films subjected to high-level electric stress in the presence of space plasma and solar radiation.
23. Solar Array Materials evaluated the synergistic effects of space on mechanical, electrical, and optical properties of solar array materials, such as solar cells, cover slips with various anti-reflectance coatings, adhesives, encapsulants, reflector materials, substrate strength materials, mast and harness materials, structural composites, and thermal control treatments.
24. Advanced Photovoltaic Experiment investigated the space effects on new solar cell and array materials and evaluated their performance and measured long-term variations in spectral content of sunlight and calibration of solar cells for space use.
25. Critical Surface Degradation Effects on Coatings and Solar Cells Developed in Germany investigated the radiation and contamination effects on thermal coatings and solar cells, with and without conductive layers, and provided design criteria, techniques and test methods for the control of space and spacecraft effects.
26. Space Aging of Solid Rocket Materials determined the space effects on various mechanical and ballistic properties of solid rocket propellants, liners, insulation materials, and case and nozzle materials.

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Science

27. Interstellar Gas analyzed the interstellar noble gas atoms (helium and neon) that penetrate the heliosphere near Earth.
28. High-Resolution Study of Ultra-Heavy Cosmic-Ray Nuclei studied charge and energy spectra of cosmic-ray nuclei, superheavy nuclei, and heavy anti-nuclei to help understand the physical processes of cosmic-ray nuclei production and acceleration in interstellar space. It also obtained data on nucleosynthesis.
29. Heavy Ions in Space investigated three components of heavy nuclei in space: low-energy nuclei of nitrogen, oxygen, and neon; heavy nuclei in the Van Allen radiation belts; and ultraheavy nuclei of galactic radiation.
30. Trapped-Proton Energy Spectrum Determination measured the flux and energy spectrum of protons trapped on Earth's magnetic field lines as part of the inner radiation belt and examined neutron and proton radioactivity, microsphere dosimetry, flux measurement by ion trapping, and elemental and isotopic abundances of heavy cosmic ray nuclei.
31. Measurement of Heavy Cosmic-Ray Nuclei measured the elemental and isotopic abundances of certain heavy cosmic-ray nuclei and of chemical and energy spectra for particles.
32. Linear Energy Transfer Spectrum Measurement measured the linear energy transfer spectrum behind different shieldings, which were increased in small increments to provide data for future spacecraft designs and other LDEF experiments.
33. Multiple Foil Microabrasion Package provided a passive evaluation of the near-Earth micrometeoroid environment.
34. Meteoroid Impact Craters on Various Materials studied the impact microcraters made by micrometeoroids on metals, glasses, and minerals made into thick targets.
35. Attempt at Dust Debris Collection With Stacked Detectors investigated the feasibility of using multilayer, thin-film detectors as energy sorters to collect micrometeoroids—if not in original shape, at least as fragments suitable for chemical analysis.
36. Chemistry of Micrometeoroids conducted a chemical analysis of a significant number of micrometeoroids for data on density, shape, and mass flux.
37. Secondary Ion Mass Spectrometry of Micrometeoroids measured the chemical and isotopic composition of certain interplanetary dust particles for most expected major elements.
38. Interplanetary Dust measured the impact rate and direction of micrometeoroids in near-Earth space.

Table 3–68 continued

39. Space Debris Impact exposed passive targets to impacts by meteoroid and artificial space debris to determine the type and degree of damage expected on future spacecraft.
40. Meteoroid Damage to Spacecraft gathered examples of meteoroid impact damage to typical spacecraft components to help establish designs that would reduce the effects of meteoroid damage to future spacecraft.
41. Free-Flyer Biostack investigated the biological effectiveness of cosmic radiation, especially individual very heavy ion effects, including a quantitative assessment of the human hazards of heavy ion particles in space to establish radiation protection guidelines for human and biological experiments in spaceflights.
42. Seeds in Space Experiment evaluated the survivability of seeds stored in space and determined possible mutants and changes in mutation rates.
43. Space-Exposed Experiment Developed for Students used seeds returned from the Seeds in Space Experiment in a national education program for several million students in science and related subjects.

Electronics and Optics

44. Fiber Optics Space Effects Experiment investigated approaches and selected components of spacecraft fiber-optic transmission links to evaluate space radiation in terms of permanent degradation and transient (noise) effects.
45. Passive Exposure to Earth Radiation Budget Experiment Components measured solar and Earth-flux radiation to provide information on the amounts and sources of radiation and how it is influenced by such environmental phenomena as the “greenhouse effect” that may be unduly warming Earth’s atmosphere.
46. Holographic Data Storage Crystals tested the effect of space on electro-optic crystals for use in ultrahigh-capacity space data storage and retrieval systems.
47. High-Performance Infrared Multilayer Filters and Materials exposed to space radiation infrared multilayer interference filters of novel design, construction, and manufacture and used to sense atmospheric temperature and composition.
48. Pyroelectric Infrared Detectors determined the effect of launch and space exposure on pyroelectric detectors.
49. Thin Metal Film and Multilayers tested the space behavior of optical components (extreme ultraviolet thin films, ultraviolet gas filters, and ultraviolet crystal filters).
50. Vacuum-Deposited Optical Coatings investigated the stability of several vacuum-deposited optical coatings used in spacecraft optical and electro-optical instruments.

Table 3–68 continued

	51. Ruled and Holographic Gratings investigated the stability of various ruled and holographic gratings used in spacecraft optical and electro-optical instruments.
	52. Optical Fiber and Components examined the radiation effects of fiber-optic waveguides that have become important components in new communications systems, opto-electronic circuits, and data links. Comparisons of radiation-induced damages in flight with samples irradiated in laboratory tests would determine the validity of irradiation tests with radioactive sources.
	53. Solar Radiation Effects on Glasses determined solar radiation and space effects on optical, mechanical, and chemical properties of various glasses.
	54. Radiation Sensitivity of Quartz Crystal Oscillators gathered data on the prediction and improvement of quartz crystal oscillator radiation sensitivity and compared space radiation effects with results from a transmission electron microscope.
	55. Fiber Optics Systems assessed fiber-optic data link design performance for application in future spacecraft systems and documented and analyzed space effects on link and component performance.
	56. Space Environment Effects examined the effects of space exposure on advanced electro-optical sensor and radiation sensor components.
	57. Active Optical System Components measured space effects on the performance of lasers, radiation detectors, and other optical components to identify any degradation and to establish guidelines for selecting space electro-optical system components.
Orbit Characteristics:	
Apogee (km)	483
Perigee (km)	473
Inclination (deg.)	28.5
Period (min.)	94.3
Weight (kg)	9,707
Dimensions	Diameter of 4.3 meters; length of 9.1 meters
Shape	Twelve-sided structure
Power Source	LDEF had no power system. Any experiment that required a power or data system provided its own.
Prime Contractor	Langley Research Center
Results	Because LDEF was left in orbit much longer than anticipated, NASA officials estimated that 70 percent of the experiments had been degraded significantly, 15 percent were enhanced by the extended stay, and another 15 percent were unaffected.