Roger D. Launius

NACA TO NASA TO NOW

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On the back cover: NASA research pilot Bill Dana takes a moment to watch NASA's NB-52B cruise overhead after a research flight in the HL-10 heavyweight lifting body, 15 September 1966. Photo credit: NASA.

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Preface and Acknowledgments

"Happiness is a rendezvous mission," astronaut Kevin Chilton said about the successful recovery, repair, and redeployment of the Intelsat VI communication satellite during a 13 May 1992, record-setting extravehicular activity (EVA) by the STS-49 Space Shuttle crew. The first ever three-astronaut spacewalk by Rick Hieb, Tom Akers, and Pierre Thuot, came after two earlier attempts to capture a 4.5-ton communications satellite and maneuver Intelsat VI into the cargo bay of Endeavour. STS-49 had launched on 7 May with the rescue of Intelsat VI as its primary objective; it had reached the spacecraft three days later but failed twice to capture the satellite. After the second attempt, NASA Administrator Daniel S. Goldin joked that if they could not wrangle the bulky spacecraft, perhaps they should think twice about returning to Earth. "That was a pretty low point," said Mission Commander Dan Brandenstein. "We thought we'd lost this $150 million satellite." Upon successfully capturing Intelsat VI, they played on the famous Apollo 13 comment, "Houston, I think we've got a satellite!" In all, the crew undertook four spacewalks, totaling 25 hours, 23 minutes, to perform their mission, with the triumphant three-man spacewalk as one of the most memorable in the history of spaceflight. In the end, they were hailed as heroes.[1]

Dan Brandenstein remembered those few days wrangling Intelsat VI during STS-49 as "one of those missions from hell," but the flight of this crew on Endeavour symbolized as much as any other the record of success of the National Advisory Committee for Aeronautics (NACA) between 1915 and 1958 and the National Aeronautics and Space Administration (NASA) since 1958. It demonstrated the drive, ingenuity, "above and beyond" attitudes, innovative problem solving, and "stick-to-it-iveness." These two federal agencies led American efforts to advance the frontiers of flight. During the lifespan of the NACA, most emphasis was on aeronautics and building the capability to travel easily around the globe, to undertake all manner of activities enhanced by that capability, and to change the nature of all the peoples of the world. Since the NACA's transformation into NASA, the emphasis became more about space exploration than aeronautics, but to this day NASA remains the preeminent organization in the world solving the problems of flight, both in the air and beyond.

Throughout its history, the NACA and NASA have been critical to America's place in the world. International competition and cooperation—commercial and military—encouraged innovation in both the space and aviation sectors. Wars, particularly World War II and the Cold War, had a motivating effect on research to enhance aerospace engineering and mass production processes. The Cold War competition with the Soviet Union forced the transformation of the NACA into NASA, and with it the beginning of the heroic age of the space race and reaching for the Moon in the 1960s. But that was not all; the easing of Cold War tensions led to the creation of cooperative projects both in air and in space, especially the touchstone of this arena in the 21st century, the International Space Station (ISS) built by a consortium of 15 nations and with a multinational crew aboard.

Overall, in the trajectory from 1915 to the present, the NACA and NASA have realized stunning accomplishments that deserve both analysis and commemoration. The federal investment made in the NACA/NASA enabled the core technologies needed to master and use ever-advanced flying vehicles in air and space. The employment and evolution of large-scale engineering techniques and methodologies have yielded important lessons for similar-scale projects in other areas. These accumulated lessons have enduring relevance—from the days of the NACA's large-scale wind tunnels, to experimental aircraft seeking ever higher and faster flight, to NASA's large-scale engineering projects involved in human spaceflight. From the Mercury, Gemini, and Apollo programs to the Space Shuttle and International Space Station and the exploration of the Moon and Mars, the lessons learned continue to guide and inform.

The results of investments in aerospace technology are everywhere around us. In no small measure, government investment in miniature electronics technologies in the 1960s and 1970s, for instance, led to the many devices we use today: personal computers, programmable watches, and the Internet. Anyone may board an aircraft anywhere in the world and reach any other place on the globe in less than 24 hours; an astronaut in theory could do it in less than 2 hours. Research and development (R&D) for our space-based system of navigation—the Global Positioning System, or GPS—has made reading a paper map obsolete. These are only a few examples among thousands. Whatever the future of flight, success still hinges on the investments in aerospace technology made today by NASA, so that in the future American capabilities may be built on firm foundations.

I must also make a comment on nomenclature. The National Advisory Committee for Aeronautics was always referred to as "the N-A-C-A" with each letter pronounced individually, never NACA as one word with a hard "C." You will see it referred to in this way throughout this book. The National Aeronautics and Space Administration, however, was almost never referred to as N-A-S-A with each letter stated individually, but as a single word, NASA. You will rarely, therefore, see the article "the" placed in front of "NASA," but always in front of "NACA." It is an oddity adhered to in government and aerospace circles.

This book began under the auspices of the NASA History Office, Contract Number NNH13AW77I, and I am grateful for this support. Without it, this book would never have been undertaken. Additionally, several key people assisted in assembling the materials for this volume and placing it in some semblance of order. For their many contributions in completing this project, I wish especially to thank the late NASA Chief Archivist Jane Odom and her staff archivists, Colin Fries and Liz Suckow, who helped track down information and correct inconsistencies, as well as James Anderson, Nadine Andreassen, Bill Barry, Steve Garber, and Brian Odom at the NASA History Office; the staffs of the NASA Headquarters Library and the Scientific and Technical Information Program who provided assistance in locating materials; Marilyn Graskowiak and her staff at the National Air and Space Museum Archives; and many archivists and scholars throughout NASA and other organizations. Many other archivists at the National Archives and Records Administration, especially at several of its Federal Records Centers and at the various presidential libraries, were also instrumental in the research for this book.

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CHAPTER 1

NACA Origins

On 17 December 1903, Wilbur and Orville Wright flew the first heavier-than-air vehicle into the history books on the sands near Kitty Hawk, North Carolina. The brothers had dressed formally for that occasion, with coats and ties. They had come from their native Dayton, Ohio, to the Outer Banks of North Carolina every year since 1900, at first flying successively larger kites and gliders, and finally a propeller-driven flyer. Their aircraft looked more like a great white sailing vessel than something that could fly. The 605-pound flyer had double tails and elevators. An engine drove two pusher propellers powered by bicycle chains, one of which crossed to make the propellers rotate in opposite directions and thereby counteract a twisting tendency in flight.

They flipped a coin, shook hands, and the winner crawled into the cradle of their experimental flyer. Orville Wright launched down the starting rail into the wind and made the first flight about 10:35 a.m., a bumpy and erratic 12 seconds in the air. He covered about 100 feet, before difficulty with the front rudder caused the machine to dart for the ground, cracking the skid under the rudder. After repairs, the brothers took turns flying three more times that first day. Wilbur made the second trial, flying about 175 feet, less than the wingspan of a Boeing 747. Then Orville came back for a third trial, which was ended by a strong gust of wind. Wilbur then took his turn for the fourth and last trip of the day, launching about noon. The flight began like the others—with the flyer pitching up and down. After about 300 feet, Wilbur got it under control and began traveling on a straight course. He flew 852 feet in 59 seconds; then the flyer began bucking again and suddenly plunged to the ground. The front rudder frame was badly broken, but the main frame remained intact. Then the wind picked it up and damaged the flyer even more seriously, and the day of flying ended.

Figure 1-1. This official seal for the National Advisory Committee for Aeronautics (NACA), established in March 1915, recreates the famous image of the Wright brothers on 17 December 1903, at Kitty Hawk, North Carolina. (NASA LRC-1990-B701_P-0 2350)

Just as Orville Wright had made that first flight at Kitty Hawk, John Daniels snapped one of the most enduring images of the 20th century, a photograph that would become an icon of American inventiveness and ingenuity. Before attempting the flight, Orville had situated on the beach a camera on a tripod aimed at a point he hoped the flying machine would reach when it left the track. Daniels timed the photograph perfectly and captured the machine as it rose 2 feet into the air. It showed Orville Wright at the controls, lying prone on the lower wing with his hips in the cradle that operated a wing-warping mechanism controlling the aircraft. It also showed Wilbur Wright, running alongside to balance the machine, just as he released his hold on the forward upright of the right wing. The starting rail and other items needed for flight preparation were all clearly visible behind the machine. Developed by Orville on his return to Dayton, this image provided the photographic proof the Wrights needed to demonstrate that they had made the first successful powered flight.

Even though Americans invented the airplane, by the time Congress established the National Advisory Committee for Aeronautics (NACA) in 1915, the United States lagged far behind the technological progress of flight that other nations routinely demonstrated. This would not do during the Progressive Era, when Americans embraced a sense of advancement and modernity, and a belief that reason and rationality could solve any problem. Social justice dominated the thinking of many concerned about the welfare of humanity. Democratic precepts energized the political scene. The first billion-dollar corporations had emerged by then—U.S. Steel had a capitalization of $1.4 billion when created in 1901—and telephones were becoming indispensable tools for business, industry, and increasingly for personal communication. Movies were a popular new form of entertainment—Thomas Edison's Motion Picture Company filmed many short films, some fictional and others documentary—and baseball reigned supreme as the "national pastime." The automobile was coming to dominate personal transportation. Most Americans still had access to horse-drawn wagons or carriages, but increasingly, gasoline-powered vehicles supplanted the venerable animal-powered ones. And everything was moving faster. Stephen E. Ambrose makes clear in his biography of Meriwether Lewis that at the beginning of the 19th century everything moved at the speed of a horse. "No human being, no manufactured item, no bushel of wheat, no side of beef (or any beef on the hoof, for that matter), no letter, no information, no idea, no order, or instruction of any kind moved faster," he wrote.[1] But the 19th century portended enormous changes in transportation. Those living in it saw the movement from horsepower to steam-driven railways, then the rise of the internal combustion engine and the automobile, and finally, at century's end, the dawning of a new age of flight.

Of course, not everything was positive. All manner of inequities existed, and many suffered prejudices of all varieties. Herbert Croly, for one, wrote in *The Promise of American Life* (1909) of the new industrial age and the new political consensus that it required a sense of social responsibility and care for the less fortunate. Croly believed that "the traditional American confidence in individual freedom has resulted in a morally and socially undesirable distribution of wealth."[2] Collective action, undertaken through societal intervention, was needed. The rise of labor unions, voluntary associations, mutual aid societies, fraternal orders, and even such benign clubs as the Parent Teacher Association (PTA) helped to shape the future. This led to national action in the New Deal of the Great Depression in the 1930s and the campaigns for civil rights, women's rights, and a host of other initiatives to create a more just and equitable society.

Establishing the National Advisory Committee for Aeronautics

Croly might have been surprised by the NACA's collective approach to developing the technology of flight, but it was less of a stretch than previously thought. It was based on the belief that a brighter future could be achieved, and it used the power of the federal government to achieve it. Advocates believed that flight could serve as a democratizing influence. From ease of transportation to the potential of airplanes to render war obsolete—yes, advocates did make that argument—the world would change for the better through this effort. One could argue that the defining technology of the 20th century was the ability to fly, first in the air and later in space. It seemingly altered all aspects of life from what had gone before. For the United States, that change resulted only because of the investment of the federal government. Without it, the United States would never have become the global superpower that emerged in the

20th century. While the amount of investment the United States made in flight has ebbed and flowed with the circumstances of the times, this investment has been critical to the advancement of flight technology; without it, its capabilities would have been rudimentary and perhaps stillborn. That was true in the first part of the 20th century, and it has also remained the case to the present day.

By the beginning of World War I in Europe, the U.S. government began to perceive, albeit reluctantly, the significance of aircraft in the conduct of modern warfare. As late as 1914, the United States stood 14th in total funds allocated by nations for military aviation, far behind even Bulgaria and Greece. Because of this, Congress began a buildup of aeronautical capability and created in 1914 a permanent Aviation Section of the U.S. Army Signal Corps.

The federal government took strong action to foster research and development relating to flight starting only in the second decade of the 20th century. In a rider to the Naval Appropriations Act of 1915, Congress established the NACA "to supervise and direct the scientific study of the problems of flight, with a view to their practical solution."[3] This became an enormously important government R&D organization for the next half century, materially enhancing the development of aeronautics.

The NACA was very much a product of its time, place, and circumstance. While European powers pursued organized efforts to advance technology ahead of war, Americans limped by with private initiatives. Viewing the progress in aviation being made across the Atlantic, several Americans lobbied President William Howard Taft and other senior government officials in 1911 for the "establishment of a national aeronautical laboratory." They intended to supplant the hobbyist barnstormers and daredevils with serious efforts to advance and use this new technology. They might have been successful had it not been for a leak to the media about the effort.[4]

On 10 April 1911, the *Washington Star* reported details about a plan to establish a national laboratory under the auspices of the Smithsonian Institution. From the perspective of many advocates, assigning the Smithsonian this responsibility made sense. It had a history of flight experimentation, and Samuel Langley's laboratory near the Smithsonian's "Castle" on the National Mall still existed. Langley had been interested in aviation since the 1880s and had experimented with smaller-scale flying machines. Smithsonian Secretary Langley had received $100,000 from the War Department for his experiments at virtually the same time that the Wrights were inventing the airplane and was undertaking unsuccessful tests in the Potomac River just a few days before the Wrights' first successful flight at Kitty Hawk. The Smithsonian was just about as apolitical as any organization in Washington, and advocates believed that might soothe vested interests. It failed to do so. The military weighed in against this initiative—arguing that they needed to control their own R&D—and this had a chilling effect on the idea in Washington. This bureaucratic infighting prompted Taft to shy away from the cause, and it promptly died of neglect.

The next year, Albert F. Zahm, a professor of mechanics at Catholic University in Washington and an aviation researcher in his own right, revived the idea of a national laboratory led by the Smithsonian.[5] Others weighed in, although they seemed less interested in fostering a critical role for the Smithsonian. For instance, Richard C. MacLaurin, president of the Massachusetts Institute of Technology (MIT), endorsed the need for a national aeronautical laboratory, adding that success would only come "by attacking the problems that remain with the patience and persistence of the scientific spirit." He thought, however, that an educational institution such as MIT might be superior to the Smithsonian, affording, as he commented, an opportunity to engage "experts in all departments of science and engineering that have any bearing on aviation."[6]

Captain W. Irving Chambers, the Secretary of the Navy's Special Adviser on Aviation, added his endorsement to Zahm's proposal in Chambers's "Report on Aviation" published as Appendix I to the *Annual Report of the Secretary of the Navy for 1912*. He cited the European example of aeronautical progress: "The work of established aerodynamic laboratories has transported aeronautics generally into the domain of engineering, in consequence of which aviation has reached a stage of development wherein the methods of scientific engineers have replaced the crude efforts of the pioneer inventors."[7] He emphasized that the only way for the United States to gain true knowledge in this arena was to undertake "systematic, thorough, and precise investigation of new ideas, or of old ideas with new applications, with the specific intention of discovering laws and formulas for advancing the progress of aerial navigation." He also suggested that the British model of an advisory committee—there were no American models—would be a reasonable way forward in achieving this objective. It could "be representative of other Government departments" in order to help mitigate the bureaucratic infighting that had stifled other initiatives.[8]

Chambers was willing to place this new entity within the Smithsonian, calling it "an ideal institution which will coordinate the work, not only for the best interests of commerce and business, but for the best interests of the army and navy." As a coordinating body rather than a directing one, he thought this committee would not step on individual agency prerogatives so much as ensure cooperation and knowledge management. While the government would provide seed money, Chambers believed that the laboratory could become largely self-sufficient over time. His model for this national laboratory was the Smithsonian Institution as a public-private partnership.

Taft did not act on this proposal until he was a lame duck as President on 19 December 1912, appointing a 19-person National Aerodynamical Laboratory Commission chaired by Robert S. Woodward, president of the Carnegie Institute of Washington. Chambers took a seat on the commission as one of seven members from the federal government; so did Albert Zahm, one of 12 members from the private sector. Congress appropriated a small amount of funding to support the activities of the Woodward Commission, and it began meeting just as Woodrow Wilson took office. At its first meeting on 23 January, Congress began drafting legislation that would establish an advisory committee based on Chambers's earlier plan, although after interagency disagreements they dropped the idea of making it a unit of the Smithsonian Institution. Infighting over the placement of the organization and its mandate for research—theoretical aerodynamics versus practical R&D—derailed the proposal.

Again, a major part of the challenge revolved around the question of whether the Smithsonian should have suzerainty over the new organization. Advocates of one agency or another disagreed. While no consensus on the creation of an aeronautical laboratory emerged in the United States, the outbreak of conflict in Europe changed the nature of the debate in 1914. Because of this situation, Congress finally decided to act; it emphasized the committee aspects of the effort and provided a mere $5,000—still only about $130,000 in 2020 dollars—for the first year of operations. Sentiment for some sort of center of aeronautical research had been building for several years, of course, but it was only the experience of war in Europe that led to specific action. Congress passed enabling legislation for the National Advisory Committee for Aeronautics (NACA) on 3 March 1915 as a rider to the Naval Appropriations Act. This served as a subterfuge to get the organization established, but also to avoid the debate a formal bill would require. This new federal agency had its first meeting in the Office of the Secretary of War on 23 April 1915, with representatives from universities, the military, and several other federal agencies.

Beginning Operations

The NACA's creation was, at best, a political compromise. The enabling legislation did not call specifically for a national laboratory, although that was the desire of several advocates of the new organization. President Wilson sought to maintain strict neutrality concerning the European war and feared that combatants might take this as a belligerent act. Instead, it adopted the advisory committee approach with little in the way of a mandate to undertake much of anything. The committee might, once consensus emerged on a problem relating to flight in need of a solution, propose on an ad hoc basis research

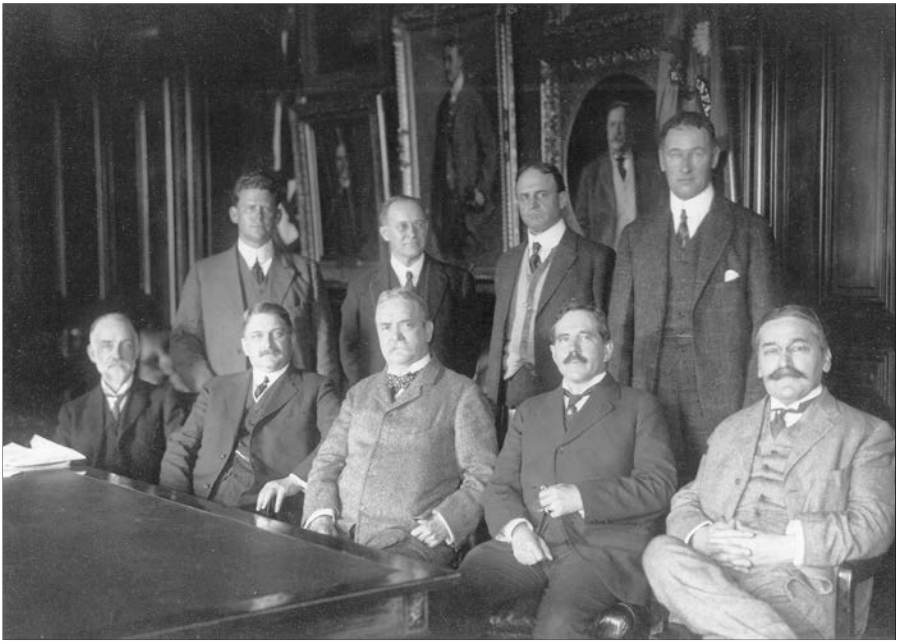

Figure 1-2. This first meeting of the NACA took place in the Office of the Secretary of War, 23 April 1915. Seated (L–R): Dr. William Durand, Stanford University; Dr. S. W. Stratton, Director, Bureau of Standards; Brig. Gen. George P. Scriven, Chief Signal Officer; Dr. C. F. Marvin, Chief, United States Weather Bureau; and Dr. Michael I. Pupin, Columbia University. Standing (L–R): Holden C. Richardson, Naval Instructor; Dr. John F. Hayford, Northwestern University; Capt. Mark L. Bristol, Director of Naval Aeronautics; Lt. Col. Samuel Reber, Signal Corps. (NASA LRC-1950-B701_P-66034)

to be undertaken in an existing government agency or university laboratory. Authorizing investigation but not sanctioning action at best served as a stopgap. For several years after its creation, NACA leaders worked at the mundane task of establishing a headquarters in Washington and sowing the seeds for establishing its own laboratory for aeronautical research among capital city politicos and senior executives.

From a minuscule headquarters in Washington, DC, occupying offices in the Navy building, the NACA's senior official George W. Lewis from 1919 (Director of Research after 1924) until 1947 guided the agency between the bureaucratic prerogatives of various agencies with differing visions of what the NACA should be doing. His quietly effective approach helped to fundamentally shape the course of aeronautical research and development in the United States for more than a quarter century.

Lewis and his assistant, John F. Victory, the first employee hired by the NACA in 1915, effectively lobbied in Washington for the new agency's needs.

Figure 1-3. George W. Lewis was one of the two most significant figures in NACA history through World War II. He became the NACA's Director of Aeronautical Research in 1924 and served until he retired in 1947. The NACA's Cleveland laboratory bore his name between 1948 and 1999. (NASA 1998_00215)

Both men proved adept at working influential patrons at cocktail hours in such bon vivant watering holes as the Army Navy Club and the Cosmos Club. They often won approval even for initiatives that seemed likely to fail due to political infighting. Both Lewis and Victory established a legacy of effective leadership in the NACA. They would be followed by many others who continued this guidance in aeronautical R&D.

Lewis began recruiting young scientists, engineers, and mathematicians to enter federal service, usually for less pay than they could find elsewhere. He promised them, however, an opportunity to perform cutting-edge research and to try sometimes hare-brained ideas that had little immediate commercial application. These efforts worked, and by the time that the NACA was transformed into NASA in 1958, it had developed an exceptionally positive reputation for innovative aeronautical research and development.

A leading figure serving on the advisory committee, William Frederick Durand, provided steady leadership as the NACA began operations. An internationally known teacher and researcher in aeronautical propulsion during the first half of the 20th century, Durand had created the aeronautical engineering program at Stanford University in the first part of the century. He was appointed a member of the committee in 1915 and served until 1933, and chaired the committee in 1917–18. Over the years, most of the research conducted under NACA auspices was done in its own facilities, but until the first laboratory was constructed at the end of World War I, the committee relied on contracts to educational institutions to undertake work. Durand's research team at Stanford led the way with its NACA experimentation on propeller shapes. This would have been considered a conflict of interest at a different time, but amid World War I and the lax regulatory environment of the era, no one questioned it.

This and other contracts paid off; the NACA's research on aircraft engines and propellers was the first major success of the organization and helped develop the Liberty engine, the major contribution the United States made to aeronautics in World War I.

Becoming a Research Organization

At the end of World War I, the NACA was still very much in the process of establishing its identity. While Lewis, his staff, and committee members had aided the war effort, critics abounded because it still had no R&D capability. Some criticized it for rolling with the exigencies of the political crisis du jour rather than expending more energy on establishing R&D facilities. Leigh M. Griffith, an early NACA technical employee, voiced the concern that the NACA was loose and disorganized and that it had not developed an effective statement of the "nature of the services that this Committee is endeavoring to render, or is capable of rendering.... Until it is known what we are trying to do, it is impossible to formulate any system or build any organization for the doing of that thing."[9]

Those criticisms were quite valid, especially in the early years of the agency. The reality was that while virtually everyone believed the United States needed an organization to oversee the development of aeronautical technology, they fundamentally disagreed over the form it should take, the authority it could hold, the chain of command in which it should reside, the budget it might oversee, the breadth of its activities, and the reach of its prerogatives. After considerable debate, the NACA gained responsibility for undertaking aeronautical R&D, an expansion of its role from World War I.

Establishing the Committee Structure

The advocates on behalf of the NACA had always intended it to operate largely as an advisory committee consisting of industry, academic, and military members, but it needed to develop a strategy. George Lewis began to implement an approach by establishing the direction of the NACA's research procedures. A reasonably stable approach evolved by the 1920s and remained virtually the same until World War II. As the strategy came to be implemented, the NACA leadership regularly solicited and accepted suggestions for research projects from several sources. While the military services provided the bulk of the suggestions, other government agencies, especially the Bureau of Standards and the Department of Commerce, also contributed requests. The NACA staff, most often technical personnel, also offered ideas. Sometimes outside sources, especially the aeronautical industry, asked for specific research on thorny problems requiring a solution.

The NACA Main Committee had 12 members drawn from throughout the United States. It met semiannually in Washington, DC, serving in the truest sense of the term in an advisory capacity. Additionally, the NACA's Executive Committee of seven members involved itself more fully in the agency's activities since these individuals resided in the Washington area. They closely scrutinized the NACA's activities and oversaw the research agenda. Like so much else about the NACA, this approach worked well despite its informality and ad hoc nature. Indeed, the NACA structure became quite complex and confusing over time, with numerous committees within committees and subcommittees until the layering was almost impossible to decipher for all but the most dedicated sleuth.

Those holding positions in the NACA structure read like a who's who of aviation. On 29 January 1920, for example, President Woodrow Wilson appointed Orville Wright to the NACA's main committee. At other times, such luminaries as flyer Charles A. Lindbergh, Smithsonian Secretary Charles D. Walcott, science entrepreneur Vannevar Bush, MIT engineering professor Jerome C. Hunsaker, and air racer and military officer James H. Doolittle served on the main committee.

Thereafter, NACA officials appointed subcommittees to deal with specific technologies. During World War I, the NACA formed 32 separate subcommittees covering various aspects of aerodynamics; airfoils; propulsion; aircraft construction, structures, and materials; operating problems; air navigation; communications systems; and a host of others. Sometimes these subcommittees covered broad, sweeping subject areas, but just as often they dealt with minute issues. A subcommittee on aeronautical torpedoes, for example, was certainly an appropriate topic of consideration, but others on other types of munitions competed for the attention of the overall NACA leadership.

Within a year of taking over as director of research in 1918, George W. Lewis reorganized the committee structure to rationalize its functioning. Reflecting technological questions, Lewis's new structure focused the NACA by the early 1920s on new and more ambitious research: to promote military and civilian aviation through applied research that looked beyond current needs. NACA researchers pursued this mission through the agency's development of an impressive collection of in-house wind tunnels, engine test stands, and flight-test facilities.

CHAPTER 2

Making a World-Class Aeronautics R&D Organization

It looked more like a submarine than anything else, but no matter, the wind tunnel was a remarkable aeronautical research instrument. The brainchild of Dr. Max Munk, a German engineer who came to work at the NACA's Langley Memorial Aeronautical Laboratory (LMAL) in the early 1920s, the Variable Density Tunnel (VDT)—only 34.5 ft (10.5 m) long and 15 ft (4.6 m) in diameter—was the first pressurized wind tunnel in the world. This meant the VDT could achieve more realistic effects than any previous wind tunnel to show how an actual aircraft would perform under flight conditions. The NACA had it built at the nearby Newport News Shipbuilding and Dry Dock Company and shipped to Langley by rail on 3 February 1922. It put the NACA and Langley laboratory on the map and set in motion years of groundbreaking research.

The NACA gained approval to establish Langley in 1917 when Congress approved funding for a research and development (R&D) laboratory. Between 1917 and 1920, the agency's leadership scouted locations, acquired real estate, and built the first facilities at the new laboratory. It did not take long for the elements of aeronautical research—theoretical studies, wind tunnel tests, and flight research—to be implemented at Langley. The successes of those efforts brought to the NACA world renown before the end of the 1920s. The NACA's wind tunnels, especially the VDT, prompted research engineers to focus on aerodynamics.

The NACA's research reports resulting from this work proved the stuff of legend, routinely referred to by all that used them as a "bible" of knowledge about a given subject, be it propellers, airfoils, or any other aspect of flight. Later in the 1920s and 1930s, the NACA's research branched into engines, guidance and control, and materials. Although the organization never had much federal funding and carried out its mission without fanfare, the NACA built the knowledge of flight and developed aeronautical technology second to none for the United States.

Establishing the Langley Memorial Aeronautical Laboratory

While the establishment of a laboratory had not been explicitly authorized in the NACA charter of 1915, it also contained no proscription against it. This left NACA officials with an entrée for the creation of the Langley Memorial Aeronautical Laboratory. Almost immediately, NACA officials began scouting for an appropriate location for its new laboratory, deciding to collocate it with a new U.S. Army airfield near Norfolk, Virginia. Both the military and the NACA facilities were named after the Smithsonian's former secretary Samuel Pierpont Langley in honor of his contributions to aeronautics. The Army Air Service and the NACA installation shared the same runways. George Lewis commented about this location: "It has large areas of cleared land now under cultivation.... The requirements being so fully met by the area north of Hampton, your committee strongly recommends that this site be secured as soon as practicable."[1] This proved a reasonable location; it was relatively undeveloped and therefore land was available but also within a few hours of NACA headquarters in DC.

That rosy picture, however, masked the body-crushing work in Virginia's coastal marshlands to build the laboratory. Novelist Thomas Wolfe, famous for *Look Homeward Angel*, worked on the construction crew as a young man. He remembered the toil of "grading, leveling, blasting from the spongy earth the ragged stumps of trees and filling interminably, ceaselessly, like the weary and fruitless labor of a nightmare, the marshy earth-craters, which drank their shoveled-toil without end."[2] One Army observer described it as "nature's... cesspool" composed of "the muddiest mud, the weediest weeds, the dustiest dust, and the most ferocious mosquitoes the world has ever known."[3] The work was more than difficult; it proved deadly: between September 1918 and January 1919, 46 members of the work crews died during the pandemic that year.

Langley opened for business on 11 June 1920, with Henry J. E. Reid as "Engineer-in-Charge." Reid eschewed hierarchy and created an aura of collegial relations both in rhetoric and in fact. Those who experienced the NACA during that early era spoke of it in idyllic terms. Langley was a tiny organization: it numbered only 43 people at its establishment. Its researchers were able to develop their own research programs along lines that seemed to them the most productive, handle all test details in-house, and carry out experiments as they believed appropriate. Day-to-day operations registered decided informality; staff hobnobbed together in social settings, and any individual had access to the most senior leadership in the agency. This sense of freedom made it possible to recruit some of the most innovative aeronautical engineers in the world. They knew they were valued, that they had freedom to pursue research that could revolutionize the field, and that they personally could make a difference. While

Figure 2-1. These hangars at the Langley Memorial Aeronautical Laboratory were some of the first structures built by the NACA. This image from 1931 shows a Fairchild test aircraft as well as a modified Ford Model A that was used to start aircraft propellers. (NASA, LRC-1931-B701_P-05977)

the NACA as an organization would become more formalized over time, it remained committed to fostering creativity and innovation.

During the 1920s, NACA executives built a balanced research staff that pioneered novel methods of flight research; new ideas for recording instruments; and new methods and facilities for research on engines, propellers, structures, seaplanes, ice prevention, helicopters, and many other branches of aerodynamics. They developed and made use of various types of wind tunnels—variable density, full scale, refrigerated, free-flight, gust, transonic, and supersonic—the core instruments NACA engineers employed to advance aerodynamic knowledge.

Three Legs of Aeronautical Investigation

All research projects undertaken at the NACA during its early period sought to pursue investigations that promised the discovery and compilation of fundamental aeronautical knowledge applicable to all flight rather than working on a specific type of aircraft design that would appear to be catering to a particular aeronautical firm.

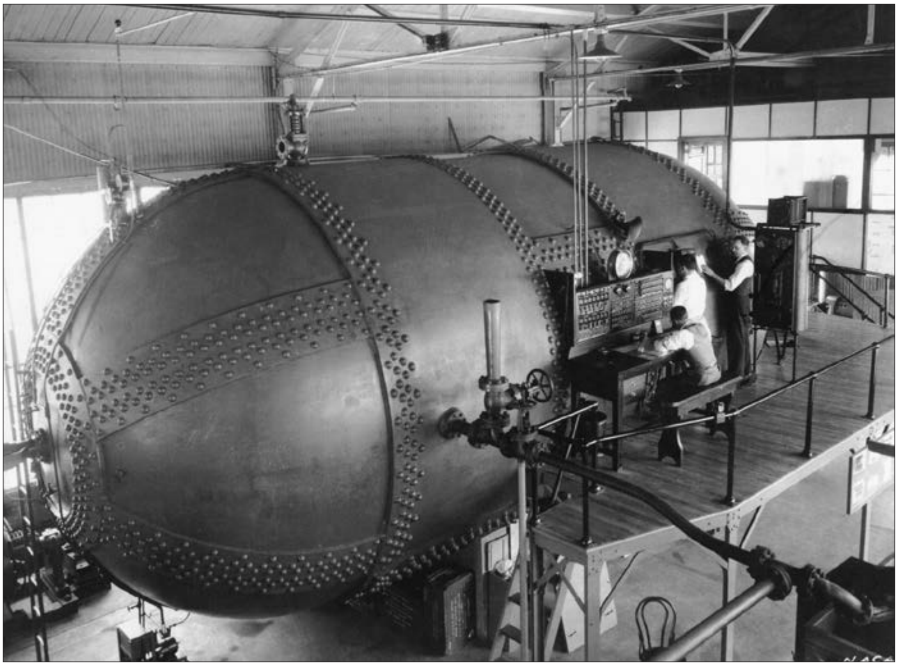

Figure 2-2. This image from 1931 shows the Langley Memorial Aeronautical Laboratory's Variable Density Tunnel (VDT) in operation. This view clearly shows the layout of the VDT's surroundings, as well as its plumbing and power systems. (NASA, EL-2002-00543)

Through this effort it became obvious—something already understood in Europe—that many revolutionary breakthroughs in aeronautical technology resulted from significant R&D investment, much of it the result of government largesse. The experience of the NACA suggests that great leaps forward in technological capability almost always required significant long-term investment in research and development, specifically research and development that did not have explicit short-term returns to the "bottom line" and might not yield economic returns in any way that could be projected. However, without that large-scale investment in technology, the United States was destined to remain a second-class aeronautical power.

The NACA developed a complex process for vetting and approving "Research Authorizations" (RA), the official license to undertake specific research at Langley or anywhere else under the purview of the NACA. Whenever requests for research came into the NACA, the Executive Committee approved, denied, or tabled them. While the NACA sought to pursue investigations that promised the compilation of fundamental aeronautical knowledge that would be available to all on an equal basis, the staff violated that rule when the military services needed a problem solved.

When a project received approval, NACA Director of Research George W. Lewis signed an RA providing the general parameters of the project and a funding limit, both of which could be changed at a future time if appropriate. Regular review of active research authorizations led to cancellation or consolidation of those that proved less productive.

Work conducted under an RA might be of short duration or could be years in the accomplishment. Short-duration work was often aimed at resolving a specific technical problem. One example of this approach was the effort to improve the aerodynamic efficiency of aircraft.

Many longer research projects took years and were redefined and given additional funding repeatedly to pursue technological questions as they emerged. A good example of a longer-term effort was Research Authorization 201, "Investigation of Various Methods of Improving Wing Characteristics by Control of the Boundary Layer," signed on 21 January 1927. It provided for broad-based research at the NACA on methods for airflow along the surface of the wings, thereby improving the aerodynamics of flight. Research took place between 1927 and 1944, making a variety of twists and turns. Those efforts were channeled at first toward solving immediate practical objectives that could be used by industry and other clients. Later, the NACA staff pursued other avenues in wing research.

Later, the Langley research staff became increasingly open to new ideas and avenues of exploration. This often required the laboratory's leadership to step in and curtail certain aspects of the RA. At the same time, this freedom enabled such research engineers as Eastman Jacobs, who became legendary at Langley for his contributions to aerodynamics, to greatly advance boundary layer control through modification of airfoil shape. Such efforts demonstrated the serendipitous nature of research and the practical benefits that could accrue from seemingly unregulated investigation. The boundary layer research by NACA engineers is still being used as the foundation for current aerodynamic design efforts.

Theory

In terms of the first leg of aeronautical research, the NACA never did develop the theoretical underpinnings of aeronautical research that rested with universities and European laboratories. While formal aerodynamics theory went back to British scholar Sir George Cayley in the early 19th century, few American researchers worked in this arena.

The one individual who made a major name for himself as an aeronautical theoretician early in the NACA's history was Theodore Theodorsen. After coming to the United States from Norway in 1924, he moved to the NACA's Langley laboratory, where he soon took over the Physical Research Division. He proved adept at both theoretical studies and helping with empirical research on such problems as the aerodynamics of thin airfoils. He went on to develop a classic theory of arbitrary wing sections as well as the basic theory of aircraft flutter and its verification. He also contributed to the theory of open, closed, and partially open wind tunnel test sections. Highly innovative in both theoretical and experimental investigation, Theodorsen recognized, advocated for, and used a succession of complex wind tunnels at Langley to test hypotheses and advance the state of the technology.

Ground Experimentation

The vast majority of the NACA's engineers were empirical researchers, and the agency gave them the best tools any research engineer could ever want: an array of flexible and highly advanced wind tunnels. This second leg of aeronautics research soon became the NACA's forte. Its wind tunnels quickly became the critical tool for advancing the painstaking work of incrementally pushing the boundaries of knowledge about aerodynamics.

Only government research establishments such as the NACA had the resources necessary to build and operate the different types of tunnels needed to pursue sophisticated research. Universities might be able to fund one or two different types of wind tunnels; industry, perhaps a few more, but only if related to applied research; but for the deep, broad-based, long-term research required to really advance aeronautical technology, a range of wind tunnels able to mimic all manner of aeronautical conditions were required. Wind tunnels were not only the most progressive research equipment available at the time, they also suited the strength created at the NACA by its engineers, painstaking research providing in-depth knowledge on every challenge tackled. The NACA solved many of the problems of flight through this effort and did so both ingeniously and cost-effectively.

Leading the wind tunnel transformation at the NACA was Dr. Max Munk, a German aerodynamicist who had studied under Ludwig Prandtl at the University of Göttingen. Prandtl had been instrumental in establishing the linkage between theory and practice in Germany during the interwar era. He sought to make airplanes more efficient, safe, and effective, and this objective found expression in the practical research of Munk. Munk arrived in the United States in 1920, went to work at Langley, pioneered the VDT, and wrote many brilliant research papers. Munk quickly assumed leadership in the construction of the most significant of Langley's early wind tunnels. He was also as much a stormy petrel at the NACA as he was a talented researcher. Munk antagonized everyone from colleagues to superiors to luminaries. He did not last long, leaving the NACA in a huff in 1926 after a dispute with the NACA's Director of Research in which Munk called him a "liar and a slanderer," among other things.[4]

These NACA wind tunnels at Langley energized the agency's groundbreaking aerodynamics research program during the latter part of the 1920s. Utilizing the unique attributes of the VDT and other tunnels, Langley engineers systematically tested dozens of aircraft wings. They created a classification system that represented a particular airfoil's geometric properties. By early in the next decade, the laboratory had fully tested 78 separate wings, each associated with an NACA numerical designator that would allow a designer to choose the best possible wing shape for a new aircraft depending on the other features of the aircraft. The results of that research are still used today in design work on planforms.

Additionally, the NACA's stunning research into the aerodynamic drag of aircraft engines made possible revolutionary advancements in aircraft efficiency and speed. The NACA engine cowling—an aerodynamically shaped cover for the engine—is the best early example of this effort. Most of the aircraft of the 1920s used mounted air-cooled radial engines, with the cylinders open to the elements to maximize cooling. Although this solved one problem, engine cooling, it exacerbated another one, drag for the aircraft. Various aircraft builders had addressed this problem by designing liquid-cooled engines covered with aerodynamic covers, again solving one problem while intensifying another, that of the weight of the aircraft.

Frustration reigned among aircraft designers: how might they solve the problems of aircraft heating, weight limitations, and drag on the airframe? In 1926, the Navy came to the NACA asking for a solution to drag on the aircraft engines. In response, Langley engineers went to work designing a metal shroud for a radial air-cooled engine that not only improved cooling but reduced drag. Led by Fred C. Weick, then a relatively young NACA engineer who went on to a distinguished career in aeronautics, they used the NACA's wind tunnels to develop a series of metal cowlings that cleanly directed airflow through an engine for cooling while improving the lift-to-drag ratio. Weick's "No. 10" cowling proved the most effective of all the designs. In 1928, with the publication of NACA Technical Note 301 detailing the results of this research, aircraft manufacturers adopted the technology for their airplanes.

While each model required slight modifications to the cowling design to maximize its efficiency, the return on investment was staggering. A cowling tailored for the aerodynamic qualities of each model cost only about $25 per airplane in 1920s dollars and saved more than $5 million for the industry through the decade. Since the whole of the NACA's budget from 1915 to 1940 did not add up to $5 million, this was an impressive success for the young research agency. Small wonder, therefore, that the NACA received its first Robert J. Collier Trophy (Named for the publisher of *Collier's* weekly magazine) for 1929 "for the greatest achievement" in aeronautical technology. The success of the cowling had less to do with finding one particular "fix" for a technical problem and more to do with reorienting engineers toward adopting standards that took into consideration the parameters of different aircraft systems and their interaction with each other. By 1929, Langley had gained the reputation as one of the most productive research facilities in the world.

Moreover, the NACA's annual budget rose drastically to $1.3 million in 1930, with the intention that this would lead to more breakthroughs in aeronautical technology. Over the next decade, the NACA constructed a variety of additional wind tunnels, some of them quite specialized in their capabilities. The most significant of these after the VDT was the full-scale (30- by 60-foot) tunnel, which became operational in 1931 at Langley. Constructed under the leadership of Smith J. DeFrance, who had experience with Langley's VDT, this became one of the agency's busiest facilities, providing the capability to analyze virtually all of the aircraft of the era. It remained in operation until 1995 and tested not only the aircraft of the 1930s through the 1990s, but also spacecraft, helicopters, wingless lifting bodies, and a variety of other exotic vehicles such as the X-15.

Flight Research

The third leg of aeronautical R&D required flight operations. This became successful in no small part because of the efforts of Edward Pearson Warner, who arrived at Langley in 1919 and organized the flight test program. Warner, one of the early graduates of the MIT aeronautical engineering program, would stay at the NACA for only a little more than a year before returning to teach. He moved between academia and government service the rest of his life and influenced virtually every policy decision affecting aviation through the World War II era.

Working with two military test pilots, Lieutenants H. M. Cronk and Edmund T. "Eddie" Allen, Warner and his research team acquired two Curtiss JN-4 "Jennies" and used them to gather data on flight characteristics with a variety of instruments to measure lift, drag, and other aspects of flight. During this flight-test program, the NACA also began developing a cadre of pilot-engineers, usually referred to throughout NACA/NASA history as research pilots. The

JN-4 flight research effort became the model for the NACA approach to aviation research from subsonic through supersonic flight.

In 1924, the NACA acquired and modified a PW-9 Army pursuit plane for flight research. John W. "Gus" Crowley took the lead. An MIT graduate, Crowley would become chief of the Langley Flight Test Section and a future NACA Associate Director for Research. He organized a flight research program to support an Army Air Service request for technical information on various aircraft wing loading, center of gravity, pressure distribution at various angles of attack, physiological effects on pilots during maneuvers, and a host of other questions. Throughout the latter half of the 1920s, flight research at Langley proceeded using a variety of aircraft types. They concentrated on pressure distribution over airframes in the earliest projects, analyzing through repetition and variation what happened to the aircraft during level flight, pull-ups, rolls, spins, inverted flight, dives, and pulling out of dives. In late 1928, engineers reported that "normal force coefficients obtained in maneuvers, pull-ups for example, are much larger than obtained from tests in steady flight or from wind tunnel tests." This led to an expansion of research to catalog these flight characteristics under different conditions.

The NACA gained fame with this work, publishing in 1929 the first seminal studies of aerodynamics of pressure distribution on aircraft, followed early the next year with a summary, "The Pressure Distribution Over the Wings and Tail Surfaces of a PW-9 Pursuit Airplane in Flight." This report set a new standard of knowledge; NACA writers announced:

> It is perhaps needless to say that crashes resulting from structural failures in the air, even though relatively rare, have a particularly bad effect on the morale of flying personnel…and on the attitude of the public toward aviation, and must be eventually eliminated if confidence in the airplane is to become deep-rooted. It is manifest, therefore, that the structural design of airplanes must be put on an indisputably sound basis. This means that design rules must be based more on known phenomena, whether discovered analytically or experimentally, and less on conjecture.[5]

By the early 1930s, the NACA's flight research program had established a reputation for excellence just as great as that of the wind tunnel work. The historian Michael H. Gorn has concluded: "First of all, its success did as much as any NACA activity to bring acclaim and reputation to this new institution. Henceforth, the military services, the universities, and the aircraft industries looked to the NACA for research leadership and innovation…. No less important, this research won for the flight research practitioners a place beside the theorists and the wind tunnel experimentalists."[6]

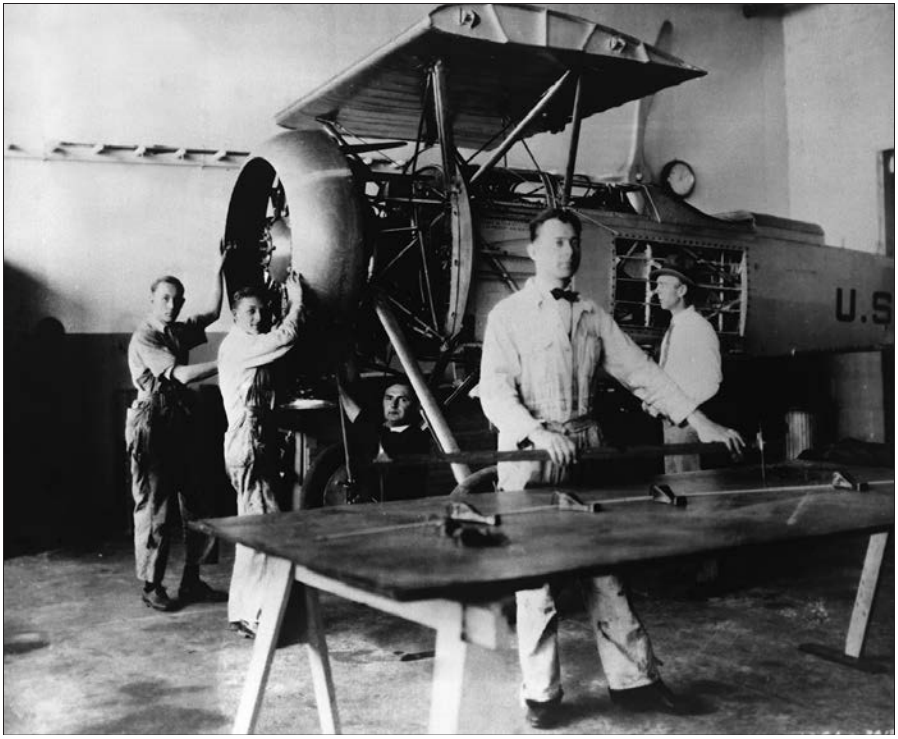

Figure 2-3. The NACA received its first Robert J. Collier Trophy for the greatest achievement in aerospace in 1929 for developing a cowling to fit over the engine that decreased drag and improved speed of the test aircraft from 118 to 137 miles per hour. This photo shows NACA technicians installing a cowling for testing in 1928. (NASA, L05584)

Pearl Young and Documenting Progress in Aerodynamics

The research that the NACA undertook all found dissemination in a complex set of technical publications that the agency made available to all on an equal basis. These research reports became the industry standard for rigorous investigation and analysis. During its history, the NACA printed more than 16,000 research reports of one type or another. These were distributed widely to a huge mailing list that included laboratories, libraries, factories, and military installations around the world. They became famous for their thoroughness and accuracy and served as the rock upon which the NACA built its reputation as one of the best aeronautical research institutions in the world.

The architect of NACA technical reporting was Pearl I. Young, who came to work at Langley in 1922 upon completing a physics degree at the University of North Dakota. After working in the instrumentation division for a few years, she realized that someone must oversee the technical reports system, which at that time was in disarray. Young took on that responsibility and led the effort until World War II. She created the multitude of documents issued by the NACA, enforced an NACA style of presentation on authors, ensured technical accuracy, and handled document distribution far and wide.

Young preached that knowledge is the product of a research laboratory, and the research report must receive special emphasis. She insisted that reports present data "tactfully, strategically, and with telling force."[7] She ensured that all publications were accurate, well organized, and effectively structured. Not to give appropriate attention to the presentation of research would ensure that the report would be neither read nor used. She enforced a harsh clarity on the technical reports process at the NACA, one that quickly paid dividends as the agency's researchers gained stature around the globe for both their groundbreaking results and their effective communication.

Young's oversight of the technical report program was always exacting, sometimes to the consternation both of NACA engineers who wanted to see their work disseminated promptly and viewed Young's efforts as bogging down the process, and of industry or military clients who wanted prompt answers to aeronautical problems. She insisted that the quality of the final product was more important than the speed with which it appeared; Young had all documents extensively vetted by engineering peers, and before finalizing any report she "checked and rechecked for consistency, logical analysis, and absolute accuracy."[8]

Pearl Young went on to other responsibilities during World War II at the NACA's Cleveland, Ohio, Aircraft Engine Research Center. She eventually moved to Pennsylvania State University to teach engineering physics but returned to NASA in 1958 before retiring in 1961. She commented late in life about the noble effort they were engaged in—separating the real from the imagined in flight—adding: "There are just as many aeronautical research problems for you to solve by the application of brains and hard work as there were on the day Orville Wright piloted the first airplane at Kitty Hawk in 1903."[9]

Model Research (and Some with Full-Sized Aircraft)

The wind tunnels of the NACA, in which models of aircraft could be tested for their flight characteristics, certainly proved critical to the advance of aviation technology in the pre–World War II era. This had been the case for any pioneering aeronautical research prior to the establishment of the NACA, and such remained the same as the history of the agency progressed.

Of course, it was the VDT at Langley that really set the NACA on a firm footing in terms of ground-based research. This success led directly to the establishment of several other wind tunnels at Langley by the latter 1920s. Another pathbreaking tunnel at Langley was the 7- by 10-foot Atmospheric Wind Tunnel (AWT), which began operations in 1930. It provided the capability to study high-lift wings and general problems of stability and control. The AWT established itself almost immediately as an exceptionally versatile research tool. Four additional wind tunnels followed, each contributing to knowledge about airfoil shapes, airframe aerodynamics, guidance and control systems, and drag reduction. These wind tunnels also aided in pursuing understanding of the pressures on airframes, the compressibility problem, and aerodynamic loads and stresses on the aircraft.

Thereafter, the NACA built another wind tunnel to test propellers. The brainchild of Director of Research George W. Lewis, the Propeller Research Tunnel (PRT) was large enough to place aircraft with their propellers operating in the test section. The PRT demonstrated its worth almost at once. In addition to propeller research, it could be used for aerodynamic drag research, and NACA engineers found that exposed landing gears contributed up to 40 percent of fuselage drag. Retractable landing gear emerged from this project as the state of the art for aircraft seeking greater speeds. PRT engineers also found that multi-engine aircraft performed best when engine nacelles were built in-line with the wing. These results influenced every major aircraft of the latter 1930s and may be seen in the shape of the DC-3 transport and both the B-17 and B-24 bombers of World War II.

In addition, the NACA built in the mid-1930s its preeminent wind tunnel before World War II, the so-called "Full-Scale Tunnel" (FST). Built under the direction of Smith J. De France, the FST boasted a 30- by 60-foot test section, with an open throat that facilitated the installation of full-size aircraft. Two massive propellers, driven by two 4,000-horsepower electric motors, pushed air through the test section at speeds between 25 and 118 miles per hour (mph). Once completed in 1931, the FST tunnel building offered an imposing site on the Langley campus with its large air-handling system and imposing brick office and research structure. Operating until the 1990s, the FST had a profound influence on the course of American aeronautical research and development. Likewise, a 19-foot pressure tunnel also helped to advance the state of the art in 1939 when completed. Virtually every advanced aircraft of World War II was tested in these two tunnels as well as many commercial vehicles and spacecraft from the NASA era.

Finally, the completion of the NACA's High Speed Tunnel (HST), with a 22-inch test section, in 1934 enabled engineers to undertake research in the Mach 1 range. In the tunnel's vertical test section, aircraft models were mounted facing downward, and a blast of highly pressurized air would provide only a minute of test time to see compressibility flows and aerodynamic flutter on airframes in high-speed conditions. This tunnel proved so useful that engineers lobbied for one with a 24-inch test section, which was put into operation late in 1934. This tunnel contained the first Schlieren photography system installed at Langley, allowing engineers to view dynamic airflows near Mach 1. This work eventually made it possible to build fighters capable of exceeding 400 mph for the United States during World War II.

These wind tunnels, from the VDT to the FST and beyond, enabled the NACA to contribute groundbreaking research in aeronautics for the United States. They were the instruments that made the agency, which was small and not well-funded, the best in the world at aeronautical R&D by the time of World War II.

Growth and Development

Aviation advocates recognized the reason for investment in the NACA's efforts before World War II. They recognized and emphasized the causal relationship between this investment and the resulting aircraft and the infrastructure supporting it. Despite this, there were different ideas over the appropriate role of government within the aviation sector and shifting attitudes over time regarding the overarching role of government R&D in the historical development of flight in the United States. During most of the NACA era, the agency's role focused on advancing key technologies for use in aircraft. The creation of a national suite of wind tunnel facilities was a clear example of this function. The government investment in this infrastructure, to the tune of several billion dollars when adjusted for inflation, serves as a reminder of the importance of the development of these crucial technologies.

The NACA faced the first years of the Great Depression in difficult circumstances, as did so many of the institutions of the nation. The NACA, caught up in a controversy for being too closely aligned with the aeronautical industry, had to be reorganized. NACA officers shifted committee assignments and compositions to reduce the influence of industry members. At the same time, the NACA instituted a policy of industry paying up front for research projects desired from the NACA. It found a ready user in industry for its wind tunnels. The success of these efforts allowed the agency to weather negative publicity and the general downturn of spending during the Great Depression.

The development of the NACA as an institution may be seen in its budget, staffing, and facilities. During its score of operations, the NACA budget gradually rose from its first-year appropriation of approximately $76,000 to over $13 million in 1935 (in 2020 dollars). New facility construction, especially wind tunnels, became increasingly significant during this period. Between 1936 and 1940, moreover, the NACA budget remained well below $60 million (in 2020 dollars) per year. It was only during the latter 1930s, when the United States began to retool for war, that Congress raised the NACA's budget to $100 million in current-year dollars.

In addition, the NACA workforce also expanded in the 1930s. Although the laboratory's research staff remained exceedingly small in comparison to the overall federal government, it grew by nearly 500 percent from 1920 to 1935. Despite its growth and importance or the expansion of the aviation industry, this investment remained an insignificant portion of the overall federal budget. In the area of aviation R&D, both the military and private sector outspent the NACA even as the civilian agency conducted considerable basic research. Only with the coming of war did the NACA workforce expand significantly, adding approximately 1,000 workers per year between 1941 and 1945, topping 5,000 individuals only in 1945 near the end of the war.

A representative engineer at the NACA's Langley may be found in Robert R. Gilruth, who arrived at the Langley Memorial Aeronautical Laboratory in Hampton, Virginia, in January 1937. Gilruth said of "Mother Langley," as its employees affectionately called it:

> I reported for duty there, and after getting fingerprinted and everything like that, I went to see the head of the Aerodynamics Division. There were really three divisions at the NACA at that time. There was the Aerodynamics Division, which is sort of self-explanatory, there was the Wind Tunnel and Flight Research Section and so on, and there was the Hydro Division, which was the towing basin. Then there was the Engine Lab, which was what it says. I was obviously an aeronautical engineer with an aviation background, so I was sent to the Aerodynamics Division.[10]

The head of that division then looked at Gilruth's résumé and sent him to work in the flight research division.

Gilruth found a center fabled for both its collegiality and its cutting-edge aeronautical research. Gilruth also found Langley highly competitive. The best aeronautical engineers in the world worked at Langley, with more arriving every month. The later 1930s and 1940s brought a heightened pace to the NACA aeronautical research program. Requests for answers to specific problems came into the NACA Executive Committee, which parceled them out to researchers for resolution. Engineers such as Gilruth worked closely with those seeking the information to ensure that they received what they needed on a timely basis. No fewer than 40 technical reports, notes, or other studies bore Gilruth's name as author between his arrival at Langley and the end of World War II. This was not uncommon.

All these employees contributed to a culture of innovation at the NACA. At every step, aeronautical innovation presented itself to those involved in developing new technology. The choice of options helped to shape the course of aeronautics, along with thousands of other choices made by designers at other locations. Gradually a consensus emerged to move in a certain direction with the technology. It did not emerge without complex interactions, differing ideas expressed, mutually exclusive models built, and minority positions eventually discarded after considering different options.

A Revolution in Aeronautics

During the second half of the interwar period, significant technological and economic advances came to aviation. The NACA was responsible for several groundbreaking innovations during this period. Also during this time, congressional legislation and appropriations fueled rapid developments in the capability of aircraft in the United States. The period has been characterized as a time of a "revolution in aeronautics."

To a very real extent, aeronautical innovation is an example of heterogeneous engineering, which recognizes that technological issues are simultaneously organizational, economic, social, cultural, political, and on occasion irrational. Various interests often clash in the decision-making process as difficult calculations must be made. What perhaps should be suggested is that a complex web or system of ties between various people, institutions, and interests shaped aircraft as they eventually evolved. These ties made it possible to develop aircraft that satisfied most of the priorities, achieving an optimum if not elegant solution.

The NACA's efforts contributed to the development of the first modern airliners. The Boeing 247, based on a low-wing, twin-engine bomber with retractable landing gear, accommodated 10 passengers and cruised at 155 miles per hour. It paved the way for the airplane that represented the revolution in ways unseen before. The Douglas Aircraft Company's DC-3 was the most prevalent commercial aircraft developed before World War II. Inaugurated in 1932 as a contract for Transcontinental and Western Airlines (TWA), it was a new all-metal, mono-winged, airliner. As a result of this, the famous Douglas Commercial (DC) series began. The DC-1 prototype of 1932 became the DC-2 that filled the TWA order and then emerged in 1936 as the revolutionary DC-3 commercial transport. It accommodated 21 passengers while cruising at 180 miles per hour. It was an instant success. Between 1937 and 1941, Douglas delivered 360 DC-3s to the airlines. In all, Douglas built 803 commercial DC-3s; they were the mainstay of airlines around the world for a generation. This airplane, with its efficient engines, favorable lift/drag ratio, high payload capability, relative comfort, and ease of operation, helped make passenger aviation profitable without government airmail contracts.

Such aircraft made possible the proliferation of air transportation in the United States and the creation of transcontinental airlines. It also made possible the development of modern military aircraft. The NACA's place in the fostering of this "revolution in aeronautics" cannot be underestimated. Although much more in federal dollars was spent by the U.S. military on aeronautical R&D, a significant "bang for the buck" was clearly present with the NACA. In the chapters that follow, several of the NACA's contributions to aeronautics will be discussed.

CHAPTER 3

Defeating Fascism

In May 1944, the angular and dour John F. Victory, Executive Secretary of the NACA, sat down at his desk and penned a letter describing his activities to support the effort to defeat the Axis in World War II. "Never was life more interesting," he told his friend Porter Adams. "Never have I been so busy. I take a keen delight in getting work done and we are rendering service of genuinely great value to the war program."[1] He understated the magnitude of the task. During World War II the NACA added more laboratories and expanded its already considerable capabilities for less basic research and more developmental work. During this period, a major transformation took place in the agency; it accommodated the needs of the armed services and contributed to a discussion of postwar approaches toward aeronautical R&D.

Voices of Warning

The NACA had steadily pursued its research agenda until the first part of 1936 when John J. Ide, the NACA's European representative since 1921, fired off an alarming report on the state of aeronautical science on that continent. Ide, the sometime technology expert, sometime intelligence analyst, and sometime expatriate socialite, reported from his office in Paris on greatly increased aeronautical research activities in Great Britain, France, Italy, and especially Germany. He observed that new and quite modern wind tunnels were being erected to aid in the development of higher performing aircraft and suggested that the NACA review its own equipment to determine if it met contemporary demands. Charles A. Lindbergh, an Executive Committee member living in seclusion in England, confirmed Ide's report in a May 1936 letter to Committee chairman Dr. Joseph S. Ames.

Ide and Lindbergh saw the same ramping up of aeronautical activities in Nazi Germany. In part because of these warnings and in part because of an

Figure 3-1. NACA research pilots stand in front of a P-47 Thunderbolt at Langley Memorial Aeronautical Laboratory in 1945. (L–R) Mel Gough, Herb Hoover, Jack Reeder, Steve Cavallo, and Bill Gray. (NASA, L42612)

invitation from the Deutsche Zeppelin-Reederei, in September to October 1936, the NACA's George Lewis led a delegation to Europe via the Hindenburg to learn about aeronautical development. While there, he toured with Dr. Adolph Baeumker, the German government's R&D head, several aeronautical facilities in Nazi Germany and was both impressed and disquieted by their activities. He learned that Luftwaffe chief and Hitler stalwart Hermann Goering was "intensely interested in research and development." With Reich marks flowing to fund accelerated experimentation, Lewis commented,

> It is apparent in Germany, especially in aviation, that everyone is working under high pressure. The greatest effort is being made to provide an adequate air fleet. Every manufacturer is turning out as many airplanes as possible, and the research and development organizations are working on problems that have an immediate bearing on this production program.

To maintain American primacy in aviation, Lewis advised, the nation should immediately start expanding the NACA's R&D capabilities.[2]

Soon after the visit to Germany, NACA leaders established the Special Committee on the Relation of NACA to National Defense in Time of War. Chaired by the Chief of the Army Air Corps, Major General Oscar Westover, this special committee began operation on 22 December 1936. Its report declared the NACA an essential agency in time of war to support the aviation development needs of the Army and Navy. It also recommended that the agency's activities should be expanded and that its workforce should remain largely civilian, though they should be exempted from a military draft.

Meantime, a real fear arose about the possibility that the United States was losing its technical edge or at least parity in military aviation because the major European powers were conducting aeronautical R&D on a wartime footing. Lindbergh again expressed his distress at advances in European aeronautics in November 1938:

> Germany's aviation progress is as rapid as ever. Production facilities are tremendous and new factories are still being built. Germany is ever today as supreme in the air as England is at sea, and I see no sign of any other nation in Europe catching up to her. I believe we should accept the fact that Germany will continue to be the leading country in Europe in aviation. She will be the leading country in the world if we do not increase our own rate of development. Even now Germany is far ahead of us in military aviation.... To give some idea of the development which is going on there, I think I need only mention the fact that the German engineers are now thinking of speeds in the vicinity of 800 kilometres per hour at critical altitude for service airplanes. Their latest bombers are now flying at more than 500 kilometres per hour.[3]

Lindbergh continued to warn of these advances in German aeronautics and to urge the NACA to redouble efforts to recapture the lead in aeronautical research and development, especially in relationship to its need to emphasize aircraft propulsion.

Institutional Blinders and the NACA's Problem of Mission

As the NACA was attempting to expand for a potential war, one of the Committee's great and recurring problems arose to almost paralyze the effort. The NACA had never been a traditional government agency. It was a committee and suffered from all the problems and benefited from all of the positive attributes of such an organization. Most significantly, it had no firm line of authority, something unusual in the world of U.S. government organizations. It also possessed no real unique place in the aeronautical world; it had a function, to be sure, but just what form that function might take and for whom the function was performed were open questions. The NACA had fought a series of bureaucratic skirmishes over these issues almost from its inception, but they arose especially in the latter 1930s as the nation prepared for war.

The Committee's mission began to be an issue in the fall of 1938, when Robert A. Millikin, head of the Guggenheim Aeronautical Laboratory, California Institute of Technology (GALCIT), in Pasadena, California, asked the federal government for help in expanding his facility's research capability to keep pace with military aviation requirements. This request aroused a longstanding NACA fear. The Committee had fought long and hard for its primary role as a research institution and had made its reputation on the basis of "fundamental research" not specifically oriented toward an aircraft design. While Millikin conceded the "fundamental research" mission to the NACA, he opened the larger question of just what research the government should fund and, by implication, the Committee's role in that research. He also stirred up several members of Congress and leaders of several government agencies to consider these issues anew.

This discussion came together in a unique way. The NACA's true strength since the 1920s had been its aerodynamics research, made possible by several wind tunnels. It had appropriately focused on areas that prompted the best use of those unique resources, and it had hired or developed leading aerodynamicists to work for the Committee. The NACA's leadership opposed any effort to circumscribe these activities. Congressman Carl Hinshaw of Los Angeles remarked:

> There seems to be a certain feeling on the part of the NACA, which I can hardly describe, but the best way to describe it is that they would like to retain a concentration of research facilities entirely within the NACA. They do not seem inclined to favor allowing these facilities to be spread out among the several qualified educational institutions. I do not just know whether it is the old question of professional jealousy or the old question of expanding bureaucracy or some other queer incomprehensible angle.[4]

Instead, the NACA pursued an expansion of its own capabilities. On 19 August 1938, a committee began studying the feasibility of a second research center. This Special Committee on Future Research Facilities, chaired by Rear Admiral Arthur B. Cook, then chief of the Navy's Bureau of Aeronautics, came forward with a recommendation to construct a new NACA facility adjacent to the Moffett Field naval air station at Sunnyvale, California. Ensconced near the West Coast aircraft industry, the new research site would be able to aid industry

Figure 3-2. The NACA's Ames Aeronautical Laboratory in the Bay Area featured the largest wind tunnel of the agency, the 40- by 80-foot tunnel. This 1947 photograph shows a test aircraft dwarfed by the tunnel's massive size. (NASA, A-16044)

as never before. John Victory made the case for this new laboratory, seen as a war measure:

> So whatever pride we may take in our present research effort, we must realize that Germany has laid well a foundation for enduring supremacy in technical development. Our plan for a second major research station at Sunnyvale was arrived at after months of sober reflection on the responsibilities facing us. We must look not only at the present, but at the situation that will exist three years from now, ten years from now. The present German advantage will have cumulative results with the passing of time unless America takes adequate measures to strengthen the research foundations for its air development.[5]

Although it took some swift action on the part of the NACA to win congressional approval, because of the saber rattling in Europe during the summer of 1939, culminating with the German/Soviet partitioning of Poland in August, the agency received permission to build the West Coast laboratory. NACA officials were proud in 1940 when the Moffett Field Laboratory opened near San Francisco as an aircraft research laboratory. It was renamed Ames Aeronautical Laboratory for Joseph F. Ames, a chairman of the NACA, in 1944. It remains operational today as NASA's Ames Research Center. This laboratory served well as a liaison to the West Coast aeronautical industry.

Meantime, Charles Lindbergh took over leadership of an NACA committee on research facilities, taking the opportunity to hammer on an area of concern that he had registered many times before, propulsion research. In a report sent to the NACA on 19 October 1939, Lindbergh "urgently recommend[ed] that an engine research laboratory be constructed at the earliest possible date, in a location easily accessible to the aircraft-engine industry."[6] Quickly agreed to by the Committee, this proposal prompted a site selection committee to begin meeting under the leadership of Vannevar Bush. In late 1940, it selected Cleveland, Ohio, near the center of the northeastern-based engine industry, as the place for the new laboratory dedicated to aircraft engine research.

The NACA had little trouble obtaining the funding for the new facility—although considerable regional politics and industrial priorities entered the episode—and in 1941, construction began. At the dedication in 1943, the NACA first named it the Aircraft Engine Research Laboratory, changing it to the Lewis Flight Propulsion Laboratory (LFPL) in 1948 (after George W. Lewis, the head of the NACA from 1919 to 1947). On 1 March 1999, Congress renamed it the John H. Glenn Research Center at Lewis Field, in honor of Ohio native John Glenn, a Marine pilot, astronaut, and Senator.

The NACA also established the Wallops Flight Center on the Eastern Shore of Virginia in 1945 as a site for research with rocket-propelled models and as a center for aerodynamic research. Finally, a temporary Langley outpost at Muroc, California, became a permanent facility known as the NACA Muroc Flight Test Unit in 1946. In 1949, it became the NACA High Speed Flight Research Station, later the Dryden Flight Research Center, and on 1 March 2014, the Neil A. Armstrong Flight Research Center, for the first astronaut to set foot on the Moon.

Doing Its Part for the "Arsenal of Democracy"

As U.S. leaders sensed the potential for war in Europe during the latter 1930s, they immediately recognized the need to strengthen the nation's air arm. General George C. Marshall recalled that it was woefully inadequate and "consisted of a few partially equipped squadrons serving the continental United States, Panama, Hawaii, and the Philippines; their planes were obsolescent and could hardly have survived a single day of modern aerial combat."[7] Harry Hopkins, President Franklin D. Roosevelt's longtime confidant, stated that "[the] President was sure that we were going to get into the war and believed that air power would win it."[8] Because of these inadequacies, in 1938 Roosevelt

Figure 3-3. Aircraft deliveries to Army Air Forces, 1940–1945.

Type	1940*	1941	1942	1943	1944	1945	Total
Very Heavy Bombers	0	0	4	91	1,147	2,657	3,899
Heavy Bombers	19	181	2,241	8,695	13,057	3,681	27,874
Medium Bombers	24	326	2,429	3,989	3,636	1,432	11,836
Light Bombers	16	373	1,153	2,247	2,276	1,720	7,785
Fighters	187	1,727	5,213	11,766	18,291	10,591	47,775
Reconnaissance	10	165	195	320	241	285	1,216
Transports	5	133	1,264	5,072	6,430	3,043	15,947
Trainers	948	5,585	11,004	11,246	4,861	825	34,469
Communication/Liaison	0	233	2,945	2,463	1,608	2,020	9,269
Total by Year	**1,209**	**8,723**	**26,448**	**45,889**	**51,547**	**26,254**	**160,070**

*Last half of year.
Source: Irving B. Holley, Jr., *Buying Aircraft: Materiel Procurement for the Army Air Forces* (Washington, DC: Office of the Chief of Military History, 1964), 554.

called for increased appropriations to build 30,000 modern aircraft since the Air Corps was operating with what could be politely called "antiquated weapons." Although he had suggested a much higher target, Roosevelt was able to obtain funding only for an additional 3,000 airplanes in 1939. Accordingly, in April 1939, when Congress passed the National Defense Act of 1940, it authorized the development and procurement of 6,000 new military airplanes, appropriating $300 million for this purpose. This was only the beginning of a massive wartime expansion of military aeronautics that led to the production of more than 10,000 bombers and 7,700 fighters, as well as a host of transport, reconnaissance, and support aircraft.

In 1938, Army Air Forces Chief of Staff Hap Arnold, MIT professor Jerome Hunsaker, and National Defense Research Committee (NDRC) head Vannevar Bush became members of the main committee, and they brought strong and ably expressed pro-military sympathies to the Committee, as well as skepticism about some of the NACA's traditional ideas about how to accomplish aeronautical R&D. Near the same time, several members of the Committee were replaced with representatives from industry who were intimately involved in the military buildup of the latter 1930s and served as able supporters of the pro-military R&D by the NACA. These individuals guided NACA research policy in the two years immediately before the United States entered World War II, and their influence throughout the war was strong. They agreed that when war came, the NACA should place its total resources at the disposal of the military, but it should also remain a civilian science and engineering institution. In this manner, the NACA became part of the “science team” that went to war, the “Scientists Against Time” that later became famous. The NACA agreed that its proper role in wartime would be to serve “as an unbiased technical advisor to any branch of the government on aeronautical matters.”[9]

Human Computers and Social Change at the NACA

To maximize the research of the NACA’s engineers as the agency geared up for the war effort, the NACA began to employ women as “human computers” to undertake calculations necessary to complete the research reports so prized by the NACA’s clients. The term “computer” had been in long-term use as a job title identifying people who performed mathematical calculations by hand or with mechanical calculators. Although there were already “human computers” at Langley prior to 1935, all of them were male, so the hiring of the first women to perform these tasks proved radical. They found themselves in a men’s club, as the only women up to that point had been in secretarial positions.

The first to arrive, Virginia Tucker, reached Hampton, Virginia, just after Labor Day in 1935 to join the laboratory’s “Computer Pool.” She found the computers organized into a central office in the Administration Building. They took the readings from the engineers and worked with them to calculate tables supporting the research. A 1942 report glowed with praise about the work of this group. Many more women would follow, with Tucker herself recruiting many of them. Reading, calculating, and plotting data from tests in Langley’s wind tunnels and other research divisions, these women played an integral role in research at the laboratory from the mid-1930s into the 1970s. They also changed the social dynamics of the NACA; for the first-time, male engineers had other professionals working with them that were not of the same gender.

World War II dramatically increased the speed of social change at the NACA. Virginia Tucker, the first, took a lead in expanding the program. She traveled to universities around the nation seeking women educated in mathematics and related fields for work in the NACA laboratories. The engineers came to rely on these computers, remarking that they calculated data “more rapidly and accurately” than the engineers.[10]

During the war, employees at Langley expanded dramatically from fewer than 1,000 to more than 5,000 by 1945. Female computers employed there, like women employed throughout the war effort, proved critical to wartime success. These computers came from everywhere, answering advertisements in trade journals and on pamphlets at colleges and universities as well as being recruited by women already at Langley. Some had friends who told them of the opportunity. Vera Huckel and Helen Willey ended up at Langley by happenstance

Figure 3-4. Female computers working at the Langley Memorial Aeronautical Laboratory in 1943. (NASA, L33025)

when they drove friends to the laboratory and heard about the computer jobs while there. They went on to careers that extended into the NASA era.

Officially classed as "subprofessionals," these were still exceptionally good jobs that only a college graduate could aspire to. By a 1942 report, Langley employed 75 female computers. A report noted: "A good number of the computers are former high school teachers. Their ages may average near 21, but there are a surprising number nearer 30 years old. There is no restriction because of marriage; in fact, some of the computers are wives of the engineers of various classification[s] here at NACA."[11] Rowena Becker had made $550 a year teaching public school in North Carolina. In contrast, she earned more than $1,400 a year at Langley. A computer's work varied somewhat based on the research project underway, but the computational work involved fundamentally reading raw data, running calculations, and plotting coordinates. They used standard slide rules, Monroe calculators, and other calculating machines to support the organization's flight research and engineering endeavors.

During World War II, African American women also found employment as computers at Langley. In 1943, the first six women—Dorothy Vaughan, Miriam Mann, Kathryn Peddrew, Lessie Hunter, Dorothy Hoover, and Kathaleen Land—had entered the NACA as female computers. Langley, located in a part of the Jim Crow South, was segregated and these computers worked in the laboratory's "West Computing Pool," where they undertook the same work as their white counterparts. Within a short time, this team consisted of more than 20 African American women. Despite the restrictions imposed by Virginia's laws, many of these women worked for years at Langley and eventually integrated into engineering groups focused on flight research and later into NASA's space operations.

The women working as computers at the NACA found both opportunities and challenges. It was a way to use their degrees in the hard sciences in professions formerly closed to them. Even so, they still found their careers hamstrung. They proved themselves, however, and many enjoyed long-term careers at the laboratory. A few used the computer position as a stepping-stone for other positions in the NACA and NASA. The NACA computers of World War II were only a few of the thousands of women employed in similar positions in technical organizations in World War II. They played an important role not only at the NACA, but also in the Manhattan Project, in various other scientific and technical organizations, and in ciphers and related fields.

The social transformation just getting under way in World War II and manifested at the NACA in the story of the female computers was not confined to questions of race and gender. The rise of a professional aerospace engineering class began to be seen fundamentally during this era as well. Perhaps the most striking feature of the first engineers hired at the NACA was how much they looked like mainstream America. At a fundamental level they were "everyman," and they were male through the end of the war. Diligence, excellence in school, and an unfaltering devotion to national duty were all that was necessary.

In part this arose because overwhelmingly the NACA's engineers were of middle-class background, often military veterans, and usually receiving educations at state universities. Most were Midwestern or Southern, the children of working-class parents who were the first members of their families to attend college. Almost all were family men, with wives and children, perhaps marrying after starting their careers at the NACA. Few were from what might be considered privileged backgrounds. The NACA of the World War II era embodied, therefore, the great transformation of the United States in the middle decades of the 20th century. It represented the rise of an educated, technological middle class.

Wartime Priorities

In one of its earliest wartime R&D efforts, the NACA focused on refining the shape of wings and bodies; developing devices to improve engine power and propeller thrust, stability and control; and protecting planes against ice and other natural hazards. These involved all types of experiments at all the NACA research institutions. The NACA periodically issued statements about its general work for the war. A January 1944 issue of *Aviation* described in proper patriotic fashion the agency's efforts and urged support for it:

> How much is it worth to this country to make sure we won't find the Luftwaffe our superiors when we start that "Second Front"? We spend in one night over Berlin more than $20,000,000. The NACA requires—now—$17,546,700 for this year's work. These raids are prime factors in winning the War. How can we do more towards Victory than by spending the price of one air raid in research which will keep our Air Forces in the position which the NACA has made possible?[12]

John Victory remarked that "[the] employees of the NACA have a big and important job to do. They are at war with similar research organizations in Germany, Japan, and Italy. It is their responsibility and they are using their technical knowledge and skill to make sure that the airplanes that are given to American and allied flyers are better and more efficient instruments of war than those flown by enemy airmen."[13]

One major R&D initiative involved drag cleanup on aircraft designs to increase speed and efficiency. Old NACA hands liked to recall how the Committee had been approached by Hap Arnold in June 1939 asking for a 400-mph fighter that could go head-to-head with the best German aircraft. The Bell P-39 had been designed as a 400-mph fighter, but it had been unable to attain that level of performance, although a stripped-down prototype had flown as fast as 390 mph at Wright Field, Ohio. During the summer of 1939, engineers at Langley investigated ways to eliminate drag on the aircraft and increase its speed. They used the full-scale wind tunnel to test various configurations and eventually came up with several modifications that pointed toward 400-mph flight under optimum conditions.

The NACA engineers increased the speed of the P-39 by about 16 percent, but because of the weight of production models, it never did fight or even fly at 400 mph. A more successful aerodynamics effort was the development of low-drag wings for the P-51 Mustang, the "Cadillac of the skies," which helped it to be one of the great fighters of World War II. During the war, Langley performed such research for 23 aircraft in production for the military. The drag cleanup it achieved provided the edge that Arnold had wanted for his fighter pilots. A 10 percent increase in performance was often enough to outrun or outmaneuver an enemy in a dogfight. This work became a significant aspect of the NACA's wartime role in applied research.

The NACA also aided in the development of three significant fighters during the war. First, Lockheed P-38 "Lightning," with its unique forked tail, was designed in 1937 for high-altitude interception. A superior aircraft in terms of performance and firepower, comparing favorably with the British "Spitfire" and German ME-109, by Pearl Harbor the service had an inventory of only 69 P-38s. This changed over time. In all, 9,536 P-38s entered service with the Army Air Forces during the war and fought in all theaters. Second, the Republic P-47 "Thunderbolt" became one of the most significant fighters of the war. By January 1944, approximately 40 percent of U.S. fighter groups serving overseas were equipped with it. Designed in 1940, the P-47 mounted six to eight 50-caliber machine guns and six 5-inch rockets. An excellent escort plane for bombers, it was also a superior ground attack aircraft. By May 1945, 5,595 P-47s were in active service with the Army Air Forces in all theaters.

Finally, the last U.S. fighter that saw heavy service in World War II was the North American P-51 "Mustang." Prior to the war, many bomber enthusiasts had believed that their armadas would be invincible to attack from enemy fighters, a theory that was quickly dispelled during the strategic bombing campaign in Europe. Accordingly, fighters were employed as escorts for the bombers, but none had enough range to stay with the bomb groups over Germany. The P-51 was the direct solution. It was designed initially for the British in 1940, with the Army Air Forces taking little interest until 1942. The first American group was equipped with P-51s in November 1943. It proved so successful in merging performance, range, and armament that by the end of the war 5,541 P-51s were in the Army Air Forces inventory. Along with the P-38 and P-47, the P-51 carried the brunt of the fighter missions for the Army Air Forces in all but the opening days of the war.

One area where the NACA failed to make an impact was in the development of jet propulsion, arguably the most significant aeronautical innovation during the war. A relatively simple engine in its principles, the jet required a unique combination of metallurgical capability, cooling and velocity control, and an unconventional understanding of Newton's third law of motion. The NACA, as well as many other aeronautical research institutions, had dallied with the concept in the 1920s and abandoned it because the combination of factors required to make it a viable option were not present. Whereas other individuals and agencies returned to the concept periodically thereafter and found success in its development at least by the mid-1930s, the NACA ignored the jet propulsion problem and was notoriously left behind in jet development. It had to make a crash effort in the 1940s, in some cases literally, and get help from the British, to catch up with developments elsewhere.

Virtually everyone who has dealt with the issue of jet propulsion in the United States has asked the same question: why did the leading aeronautical nation in the world misjudge the potential of jet propulsion so badly? Those interested in the history of the NACA posit several reasons for its blinders in dealing with this subject, and their explanations represent the best wisdom available on this problem. They suggest four interrelated factors: First, few Americans were interested in tackling the jet problem because of the overall approach to aviation in the nation. Most research into the problems of propulsion was conducted by or for the engine manufacturers, and it was in their best economic interest to make incremental improvements to existing engines. Consequently, few were asking the question in the 1920s and 1930s, and the NACA saw little reason to proceed on its own. When it created a special committee under the leadership of Stanford University's William F. Durand to study jet propulsion in 1941, aircraft industry representatives were explicitly omitted because they were economically wedded to the propeller.

Second, in contrast to European renegade jet engineers like Britain's Frank Whittle and Germany's Hans von Ohain, no Americans perceived that the combination of compressor and turbine was uniquely suited as a power plant for flight. Whittle and von Ohain were drawn to the turbojet because its simplicity and unique characteristics made it a system ideally adapted for the airplane. Although the NACA had some of its engineers investigate jet power, they were exploring avenues, such as the Campini ducted-fan power plant, that really had extraordinarily little practical application, and when their work hit a dead end, the Committee terminated the research. No one in America, it seems, grasped the potential of the turbojet until Hap Arnold returned from Great Britain in 1941 with plans for the Whittle engine and a collective light bulb went on over the head of the NACA and other American R&D organizations.

Third, the economics of aeronautical R&D weighed against the NACA's heavy involvement in the development of the jet engine. Because of its size, the NACA had always been forced to pursue research questions upon which it was uniquely suited to make significant contributions. The NACA engineers made conscious decisions to work in directions that might be more immediately productive. Jet propulsion research was, for many of them, a luxury they could not afford to pursue even if they had thought it worthwhile. The Langley facility was swamped and created a "bottleneck" in R&D in the 1930s, and by the time the Sunnyvale and Cleveland laboratories opened, the wartime increase in work was in full swing.

Finally, and this is by far the most significant area of concern, there was a problem of leadership among those who were interested in aeronautical R&D that mitigated against the NACA's timely and effective research into jet propulsion. The principal clients of the NACA were the military services, and they neither grasped the potential of jet propulsion nor asked the Committee to work on the problem. In fact, to appreciate the full potential of the jet engine, individuals had to possess sensitivity to the convergence of thermodynamic and aerodynamic principles. Few Army officers, even aviators, had the technical background to grasp this situation. This was, of course, part of a broader trend in the prewar Army; it did not understand the implications of the scientific revolution that was transforming warfare through such developments as radar, jet propulsion, atomic weapons, and other similar technological developments. The American military, until the war was under way in Europe and Britain shared the Whittle engine with the United States, did not press for work in jet propulsion.

The NACA leadership was little better. It did not exploit its self-proclaimed primacy in basic research toward the theoretical studies of jet propulsion that should have been fostered. It failed to pick up on European work in turbojets, even though some professional conferences addressed these issues in the 1930s. It always possessed, it seems, a bias against engine research regardless of the type of engine. Perhaps the fact that it had built its many wind tunnels—and had developed world-leading expertise in aerodynamic research because of them—prompted the NACA to give shorter shrift to engine research. Clearly, Charles Lindbergh was piqued that the NACA was ignoring R&D of propulsion systems, and he consequently pressed for the establishment of a separate research laboratory to undertake that work. He was successful in 1940 with the creation of the laboratory in Cleveland. A failure of leadership, then, extended over the issue and fostered American complacency in the area of jet propulsion R&D.

These factors, as well as others of a more subtle nature, came together to slow American efforts in this aspect of aeronautical R&D. The British developments shook both the NACA and other American aviation agencies out of their malaise, however, and during the war significant improvements were brought both to the turbojet and to the aircraft that they would propel, for the higher speeds necessitated significant redesigns of aircraft. It was not efficient to strap a turbojet on an aircraft designed for propellers. In this way, the NACA contributed significantly during the war toward the resolution of the transonic barrier that the United States cracked in 1947.

The NACA Plans for Peace

"Jet lag" by the NACA notwithstanding, the Committee had found a useful niche for itself during World War II, but one where it was one among many organizations performing similar types of work. That was acceptable for the war

Figure 3-5. Major NACA R&D efforts of World War II.

Drag Cleanup **Lead Laboratory:** Langley

Drag cleanup took place throughout the war at Langley as well as at the Ames laboratory using their large-scale tunnels. The R&D began by putting a full-size aircraft into one of the tunnels, taking off all antennae and other items sticking out from the body, and covering the airplane surface with tape. Engineers then took measurements of this "aerodynamically smooth" airplane. Gradually, the engineers would remove the tape strips and determine the drag created by every part of the airplane. The resulting report not only identified the problems but also made recommendations on how to correct them.

Aircraft Deicing **Lead Laboratory:** Ames

Icing was long a problem with aircraft, coating wings and propellers, reducing lift, and increasing drag. It often resulted in fatal crashes. NACA researchers developed a heat deicing system that piped heated air from the engine to the leading edge of the wing. Prototypes on the B-17 and B-24 bombers proved the concept, and the modification saved the lives of countless airmen flying in dangerous weather conditions. In 1946, Langley/Ames researcher Lewis Rodert and the NACA were awarded the Collier Trophy, aviation's highest award, for this deicing work.

Engine Superchargers **Lead Laboratory:** Aircraft Engine Research Laboratory

Beginning in 1942, NACA engineers began researching the addition of turbo-superchargers to improve the altitude and speed of bombers. Adding this system to B-17 Wright R-1820 Cyclone engines made possible a fleet of true high-altitude, high-speed bombers. The NACA continued this work for the B-29, adding a turbo-supercharger to the Wright R-3350 Duplex Cyclone engine. Both projects required extensive testing in the NACA's Altitude Wind Tunnel at the engine lab.

Duct-Rumble in the P-51 **Lead Laboratory:** Ames

The P-51 was one of the critical aircraft of World War II, but a strange thumping noise coming from deep inside the airplane while in flight raised concerns that it might lead to a catastrophic failure. Ames engineers used the 16-foot tunnel to determine that the P-51's belly scoop caused disturbances in the inlet airflow and offered modifications within a matter of weeks to the scoop that cured the duct-rumble problem.

Airfoil Efficiency **Lead Laboratory:** Langley

The NACA developed a succession of low-drag airfoils that had a profound effect on the outcome of World War II. An airfoil is a typical cross-sectional shape of a wing. Airplane designers chose from hundreds of airfoils to get the maximum amount of lift-to-drag ratio. This NACA series produced more smooth laminar flow over the wing at cruising speed than ever before. For example, the P-51 gained tremendous range, speed, and maneuverability through the increase of airfoil efficiency.

Stability, Handling, and Control **Lead Laboratory:** Langley

NACA engineers introduced during the war a new set of quantitative measures to characterize the stability, control, and handling qualities of an airplane. The military readily adopted the NACA findings and for the first time issued specific design standards to its aircraft manufacturers. It was a model of collaboration between the military, the aircraft industry, and the NACA.

Spin Control **Lead Laboratory:** Langley

Both the Army and Navy required that every fighter, light bomber, attack plane, and trainer be tested in the NACA spin tunnels, using accurately scaled and dynamic models. More than 300 models were tested, and aircraft designers used the results to help minimize spinning tendencies. This work also contributed to changes in airplane tail design, a factor instrumental in helping pilots recover from high-speed dives.

Supersonic Compressibility **Lead Laboratory:** Ames

Combat pilots in high-speed aircraft experienced periodic unexplained loss of control when air flow over various portions of their aircraft exceeded the speed of sound (the airplane did not actually fly faster than the speed of sound). This often led to a steep dive. NACA engineers initiated studies; using the P-38, they added dive flaps on the wing's lower surface, enabling pilots to overcome the effects of compressibility and retain control over the airplane if it went into a dive.

Surviving Water Impacts **Lead Laboratory:** Langley

Losses of aircrews in the Pacific too often resulted from ditching disabled aircraft, prompting the NACA to investigate ways to better withstand water impacts. Using hydrodynamic and structures facilities plus a B-24 bomber, NACA researchers in 1943 measured the force of the impact on the aircraft's bomb bay doors and other structural components when ditched in the James River. This led to reinforcing the fuselage in key areas, helping to save the lives of countless aircrews.

Skipping ("Porpoising") During Takeoff and Landing **Lead Laboratory:** Langley

NACA researchers studied problems involving seaplane hulls and floats using two tow tank facilities and an impact basin at Langley. Based on this research, amphibious aircraft manufacturers added "step" or notch to break the smooth surface of the hull. The step provided two separate surfaces, one for when the seaplane was plowing through the water and a second for when it was skimming along the surface.

effort; everyone needed and welcomed all the help they could get. But it raised a specter for the agency in the postwar era. Traditionally, the Committee had specialized in fundamental research and left most development to other organizations, in the process claiming a unique role in the R&D system that was not duplicated by anyone else. This was an important distinction made by the NACA to ensure its prewar survival. Could it find the same or a similar niche in the postwar world? The NACA tried to do so, much as did the Army Air Forces, which planned for peacetime autonomy even while the war was going on, and Committee leaders sought to define the agency's relationship with the military, industry, and other research institutions in such a way as to preserve its autonomy.

It was never able to do so. The NACA had changed during the war, and even more important, its clients and the federal government overall had changed. The most serious change was, without question, the institutionalization of science and technology into virtually every aspect of government operations. World War II brought that about in a way that would not have happened until much later otherwise. This development ensured that the military services and other organizations of the government created vehicles to obtain the knowledge they believed necessary to survive in the postwar world. The model they used was not the one pioneered by the NACA, and explicit rejection of it took place even while the war was still under way. The traditional friends and clients of the NACA, the uniformed services and the aircraft industry, were generally supportive of a postwar role for the NACA, but they were less willing to turn over exclusive responsibilities for R&D to the NACA than before the war.

Equally important, the NACA emerged from the war a transformed organization. As a result of World War II, during which the NACA focused almost entirely on military R&D, the structure of the aeronautics research system in the United States changed, and the prewar NACA approach became outmoded. During the war, aircraft companies and the Army Air Forces developed a significant in-house R&D capability, and the NACA's research infrastructure became less critical. Despite expansion in its annual budget, which by 1944 exceeded the cumulative total of the Committee's appropriations from its establishment through 1940, the NACA declined in relative significance to other R&D agencies. It was easily consolidated into another institution as a result, something that Victory and other Committee leaders had always tried to avoid before the war. Regardless of these developments, World War II was an important transition point for the NACA. In the postwar era it would engage in ever more cooperative ventures, especially with the military services, and emphasize an agenda focused on developing aircraft that could go higher, faster, and farther.

CHAPTER 4

Higher, Faster, and Farther

"We just took it up and dropped it just to familiarize the pilot with the landing characteristics and stalling characteristics.… We stalled the airplane, felt it out, became accustomed to it and by that time it was time to land, to set up a pattern and come on in and land. Very nice airplane; considering it had no booster controls or flying tail on it, it reacted very well," said Chuck Yeager, who first flew faster than the speed of sound, approximately 767 mph, on 14 November 1947. Through the X-1 program, the NACA and Air Force sought to go higher and faster than any aircraft ever before.[1]

The quest for speed and altitude immediately after World War II followed an already impressive period of advancement and set the stage for a remarkable 20 years in pushing flight capabilities thereafter. During the first century of powered flight, aeronautics fired the world's imagination with three words: speed, altitude, and distance. The period between 1945 and the middle part of the 1960s was remarkable both for the advances in aeronautical technology and for the development of rocketry and the possibilities of spaceflight. The X-plane research of the era was one major element of this advance, with the NACA at the center of efforts to fly ever higher, faster, and farther. So, too, the building of a set of modern, high-speed wind tunnels pushed the NACA in the direction of those same specific R&D programs. At the same time, work on jet engine technology positioned the NACA as a central player in both high-speed research and the emerging world of jet aviation for both military and commercial purposes. Finally, it had a major role in developing rocketry as the Pilotless Aircraft Research Division (PARD) at Langley led efforts to build practical rockets leading to the coming Space Age.

Much of the direction taken by the NACA in the post–World War II era came through the leadership of Hugh L. Dryden. A veteran of a long federal career, Dryden had served as Associate Director for Aeronautics of the National

Bureau of Standards, 1918–47, but then moved to the NACA to become Research Director, a post he held until the NACA transformed into NASA in 1958. He then assumed the role of Deputy Administrator of NASA, serving until his death in 1965. As the NACA Director, he had charge of an expanding research organization with some 8,000 employees, three large laboratories, and two smaller research stations. Most important, during his tenure as NACA Director, Dryden guided the organization into pivotal R&D in high-speed flight and rocketry.

Faster Than the Speed of Sound

The NACA tackled the quest for speed first. Since the beginning of powered flight, wind tunnels had proven useful tools in understanding the characteristics of aircraft in various situations, but researchers found that as the speed and complexity of aircraft increased during World War II, these tunnels had several limitations. Signifying perhaps the greatest limitation, in the 1930s it became apparent that the transonic regime, between about Mach .8 and 1.2, could not be adequately simulated due to the physical limitations of wind tunnels. The NACA decided to use real airplanes to explore this flight regime. A succession of X-planes that the NACA flew between 1945 and the latter 1950s revolutionized knowledge of transonic and supersonic flight.

The first of these new X-planes—the XS-1 (S was for supersonic)—began as a joint program between the NACA and the Air Force to overcome the so-called "sound barrier." The "sound barrier" as a term had originated in 1935 when engineers in Great Britain used it to describe what they saw in plots of high-speed wind tunnel tests. British aerodynamicist Dr. W. F. Hilton commented: "See how the resistance of a wing shoots up like a barrier against higher speed as we approach the speed of sound."[2] This got oversimplified for public consumption, and the sound barrier entered the public consciousness, sometimes mischaracterized as an impenetrable wall that would destroy anything that approached it.

The designers of the XS-1 at Bell Aircraft Corp. shaped it like a .50 caliber bullet since there were ballistics tests indicating that high-powered bullets routinely surpassed the speed of sound. The design even incorporated a cockpit for the pilot whose canopy rested flush with the airframe. The vehicle was to be capable of flying, as stated in the aircraft's specifications, "at least 650 mph at about 20,000 feet altitude."[3] Without jet engines of sufficient thrust, the X-1 was powered by a rocket engine developed initially by Robert Goddard at a Navy research facility in Annapolis, Maryland, during World War II. At the end of the war, Reaction Motors, Inc., refined what became known as the

Figure 4-1. The Bell X-1 in flight, the first aircraft to fly faster than the speed of sound, 14 November 1947. (NASA, EC72-3431)

6000C4 rocket engine and delivered it to Bell in April 1947 for use in the XS-1. This engine burned alcohol and distilled water with an oxidant of liquid oxygen to produce a thrust of 1,500 pounds from each of four nozzles, the state of the art in combustion for the time. Even so, it could power the X-1 for only 2.5 minutes of flight before it had to return to Earth as a glider.

The X-1 project found much of its intellectual direction at the NACA's Langley Laboratory, where research engineer John Stack spent a lifetime researching the characteristics of ever-high-performing aircraft. One of the NACA's most significant engineers of the postwar era, Stack had graduated from MIT in 1928 and made a name for himself at Langley using the 11-inch induction-drive high-speed wind tunnel to chart air compressibility on airfoils. Using a Schlieren photographic system, Stack provided some of the first images of airflow over a wing, documenting in graphic fashion the air compressibility problem. When Stack's branch chief, Eastman Jacobs, presented a groundbreaking paper on this subject at the now-famous Volta Congress in 1935, it set the aerodynamicists abuzz and launched Stack on his lifelong quest for speed, altitude, and performance. Stack would go on to play critical roles in virtually every high-performance aeronautical program at the NACA and NASA until his retirement in the 1970s.

To reach an altitude sufficient for flight tests, the NACA and the Air Force employed a modified B-29 as a mother ship to carry the vehicle to an altitude of 30,000 feet before dropping it for its flight. All of this took place at the Muroc Dry Lakebed in the Mojave Desert of Southern California, an area of 300 square miles northwest of Los Angeles. Formerly a bombing and test range, the NACA established in the fall of 1946 its High-Speed Flight Test Facility collocated with the Air Force; this eventually became NASA's Dryden Flight Research Center (renamed Armstrong Flight Research Center in 2014). There a small cadre of Langley engineers lived a monkish existence in search of the holy grail of flight: speed, altitude, and distance.

The NACA researchers developed a systematic process for advancing knowledge about the transonic range. A team of pilots assigned to the project undertook one flight after another to expand the envelope of X-1 operations to ever higher speeds. They quickly reached beyond Mach .85; at that point they surpassed the end of reliable aerodynamic data. This prompted Walt Williams, leading the NACA team at Muroc, to complain of "a very lonely feeling as we began to run out of data."

The first flight of the X-1 at Muroc Dry Lake took place in August 1947, an unpowered drop test to determine the aircraft's handling characteristics. Systematically increasing speed, the principal Bell Aircraft test pilot, Chalmers "Slick" Goodlin, made 26 successful flights in the two X-1s. To increase the pace, the Air Force and the NACA stepped up flights at Muroc with one of the X-1s as a means of gaining knowledge to influence designs of planned high-performance aircraft.

The NACA's deliberate approach to flight research sometimes flew in the face of Air Force goals of flying as fast as possible as quickly as possible. The NACA's Walt Williams clashed with USAF test pilot Chuck Yeager on more than one occasion. Yeager complained that too many missions were canceled "because some instrument wouldn't work." Williams responded: "[O]ur problem, became one of maintaining the necessary balance between enthusiasm and eagerness to get the job completed with a scientific approach that would ensure success of the program."[4] The incremental expansion of the flight envelope facilitated the collection of the most research data, but every day flown subsonic meant that others engaged in supersonic flight might achieve the goal first. Yeager departed from the flight plan once on 29 August to reach Mach .85 but failed to gather the data for which the flight had been designed. He rankled at Williams's insistence that he re-fly the planned mission correctly before moving on to the next stage of the program. Thereafter Yeager felt that he was being punished by being ordered to attend the myriad X-1 technical meetings, where he was out of his depth in terms of engineering knowledge.

Regardless, Chuck Yeager made history in this program on 14 October 1947, when he became the first human to fly faster than the sound barrier in level flight. On that date the Bell X-1 achieved Mach 1.06—about 700 miles per hour—at 43,000 feet. This success was not predicated on any miraculous engineering innovation; knowledge of how this might be achieved had been honed to a high art before World War II, and it rested fundamentally on the rocket propulsion system that could propel the X-1 beyond the speed of sound. Contrary to popular conceptions, moreover, there was no sense from anyone that this could not be achieved; the U.S. Air Force was committed to building supersonic fighters as an edge over the Soviet Union, and aeronautical researchers knew beyond any doubt that no absolute barrier to supersonic flight existed.

This might explain the matter-of-fact statement of Chuck Yeager about what was accomplished on 14 October, when he addressed a conclave of aeronautical professionals in 1956: "We looked at our data and I pretty well had the flight plan down perfect, which was the most important."[5] That statement bespoke none of the excitement that has come to symbolize that day. Yeager compensated later: "Climbing faster than you can even think…. You've never known such a feeling of speed while pointing up in the sky…. God, what a ride!"[6] In all, the NACA/Air Force team made more than 80 flights with the X-1 before the conclusion of the program after 157 flights in 1951.

There are some who have claimed that Yeager was not the first human to fly faster than the speed of sound. At the same time that the X-1 research program was under way at Muroc, North American Aviation's chief test pilot, George "Wheaties" Welch, was engaged in flight tests of the XP-86—later to become the legendary F-86 fighter—at the Muroc North Base test facility operated by the Air Force. Welch made the first flight of the XP-86 on 1 October 1947, and some personnel claimed at the time and since that Welch flew faster than the speed of sound almost two weeks before Yeager in the X-1. Others, such as X-1 chase plane pilot Bob Hoover, have refuted those claims because the XP-86 was underpowered and needed a new engine in its production models to achieve supersonic flight. The highest Mach number reached by Welch in 1947, as indicated by official flight test records, was .93 during a power dive from 45,114 feet flown on 13 November. Nothing conclusive existed supporting Welch's flying supersonic before Yeager despite some who claimed to hear a sonic boom. The XP-86 did achieve supersonic flight—after being re-engined—on 26 April 1948. NACA aerodynamicist Walt Williams, who was working on the X-1 program, responded best when confronted with this claim, "show me the data."[7] No one ever has.

The X-1 program represented a major success for the NACA in its postwar efforts. Thereafter, the NACA joined the Air Force to pursue ever greater speeds in the X-1A, X-1B, and X-1E. This research led to the interceptor built for North American defense by Lockheed, the F-104 "Starfighter." It took six years after the X-1 supersonic flight before NACA test pilot A. Scott Crossfield exceeded Mach 2 in the jet-powered D-558-2 Skyrocket—in an NACA partnership with the Navy—on 20 November 1953. Only three years after that, on 7 September 1956, Air Force Captain Milburn G. Apt was killed during his first X-2 flight after he reached Mach 3.196 (1,701 mph), becoming the first person to fly at three times the speed of sound.

The original rationale behind the X-planes had been to explore a flight regime that the NACA's wind tunnels could not simulate. However, by the time the X-1 and D-558 flew, researchers had figured out how to extend ground test facilities into this realm with the slotted-throat wind tunnel, developed by Richard Whitcomb at Langley in the early 1950s. Therefore, the real value of the research airplanes lay in the comparison of the ground-based tests with actual flight results to validate theories and wind tunnel results. The fact that the first transonic flights showed nothing particularly unexpected—dispelling the myth of a sound barrier—was of great relief to the researchers. Through this effort, a difficult transonic zone had been reduced to an ordinary engineering problem. Although few people were thinking about it at the time, the results from these experiments would also be instrumental in developing spaceplanes such as the Space Shuttle.

The next step was to push through the so-called thermal barrier predicted by legendary aerodynamicist Theodore von Kármán and others. Although not related to specific velocity like the speed of sound, vehicles venturing above Mach 5 (hypersonic velocities) experienced significantly increased heating rates from friction that appeared to present a substantial problem. Between the two world wars, hypersonics had been an area of theoretical interest to a small group of researchers, but little progress was made in defining the possible problems and even less toward solving them. The major constraint was propulsion. Engines, even the rudimentary rockets then being experimented with, were incapable of propelling any significant object to hypersonic velocities. Wind tunnels also lacked the power to generate such speeds. Computer power to simulate the environment using models, what is now known as computational fluid dynamics, had not as yet even been imagined.

Hypersonic research was authorized primarily to support the massive effort associated with developing intercontinental missiles. One researcher interested in exploring the new science of hypersonics was John V. Becker at NACA Langley. On 3 August 1945, Becker proposed the construction of a new type

Figure 4-2. This 1953 image taken at the NACA's High-Speed Flight Research Station photograph shows the Douglas D-558-2 transonic aircraft being positioned under the B-29 mother ship prior to a research flight. (NASA, E-1013)

of supersonic wind tunnel capable of simulating Mach 7 conditions. With an 11- by 11-foot test section, they succeeded on 26 November 1947 to reach a stable flow of Mach 6.9 in this wind tunnel. Nevertheless, many researchers wanted to build an actual hypersonic vehicle to validate the data from the new test facilities. The large rocket engines being developed for the missile programs were possible powerplants for a hypersonic research vehicle. It was time for round two X-planes.

Seeking a Round Two X-Plane

This second round of X-plane research resulted from the desire to understand pressures and heating at exceedingly high speeds above Mach 7. In 1946, the work of German engineers Eugen Sänger and Irene Bredt reached the U.S. Navy's Bureau of Aeronautics (BuAer), changing the perspective of many about the possibility of hypersonic flight. Sänger and Bredt argued that a rocket-powered hypersonic aircraft could be built with only minor advances in technology. NACA engineers found this quite stimulating, and researchers such as John Stack and John Becker at Langley began the lengthy process of gaining approvals to explore this flight regime.

As a direct result, using the V-2 first stage with a WAC Corporal as a second stage, Americans tested hypersonic concepts at White Sands Proving Ground, New Mexico, in the latter 1940s. The V-2/WAC Corporal combination became the first manufactured object to achieve hypersonic flight. On 24 February 1949, its upper stage reached a maximum velocity of 5,150 miles per hour—more than five times the speed of sound—and a 244-mile altitude. The vehicle, however, burned up on reentry, and only charred remnants were found.

Meantime, aerodynamicists realized that the slender aircraft body suited to supersonic flight was unsuited to hypersonic flight. Rather, they found that a blunt-nose experienced much less heating than a pointed body, which would burn up before reaching Earth's surface. The blunt reentry body, discovered in 1951 by H. Julian Allen, an engineer with the NACA's Ames Laboratory, created a stronger shock wave at the nose of the vehicle and dumped a good deal of the reentry heat into the airflow. This finding was so significant, and in such contrast with intuitive thinking, that Allen's work fundamentally reshaped the course of hypersonic flight research and provided the basis for all successful reentry vehicles since.

The clear origins of the first hypersonic flight research program occurred at a meeting of the NACA inter-laboratory Research Airplane Panel held in Washington, DC, on 4–5 February 1954. The panel chair, the NACA's Hartley A. Soulé, pressed for the approval of a new research aircraft, a "round two x-plane." In late August 1954, John Becker and other researchers at NACA Langley responded to the Soulé committee's call for a new research project proposing both a new research vehicle to move higher and faster than ever before in the hypersonic realm and to explore its implication for entering space. Becker proposed two major areas to be investigated: (1) preventing the destruction of the aircraft structure by the direct or indirect effect of aerodynamic heating, and (2) achieving stability and control at extremely high altitudes, at very high speeds, and during atmospheric reentry from ballistic flight paths.

An industry competition in 1955 resulted in the Air Force awarding North American Aviation a contract to build three experimental hypersonic research airplanes, which became the X-15. The government-industry team—led by Becker, Soulé, and Walt Williams from the NACA, and Crossfield, Charles H. Feltz, and Harrison A. "Stormy" Storms, Jr., for North American—would soon become the stuff of legend. North American had accepted an extraordinarily difficult task when the company agreed to develop the first hypersonic research airplane. Eventually, some 2,000,000 engineering work-hours and over 4,000 wind tunnel hours were devoted to finalizing the configuration for what became the X-15.

X-15: Pushing the Boundaries

The X-15 would not fly until 1959, just at the point that the NACA was transformed into NASA, but there was a lot of preliminary work undertaken in the 1950s to make that program a success. No question, the quest for speed and altitude took a bold leap forward with the X-15 program, operated by NASA between 1959 and 1968. The NASA-USAF program built three X-15 test vehicles with a long fuselage, short stubby wings, and an unusual tail configuration. A Reaction Motors, Inc., XLR99 rocket engine generating 57,000 pounds (253,549 newtons) of thrust powered the aircraft. This engine used ammonia and liquid oxygen for propellant and hydrogen peroxide to drive the high-speed turbopump that pumped fuel into the engine. Because the X-15 would operate in extremely thin air at high altitudes, conventional mechanisms for controlling the aircraft were insufficient, and the aircraft was equipped with small rocket engines in its nose for steering.

The X-15's designers anticipated that their biggest problem would be the intense heat that the aircraft would encounter due to the friction of air over its skin. The upper fuselage would reach temperatures over 460 degrees Fahrenheit (F). But other parts of the aircraft would reach temperatures of a whopping 1,230 degrees F, and the nose would reach a temperature of 1,240 degrees F. Designers chose to use a high-temperature alloy known as Inconel X, which, unlike most materials, remained strong at high temperatures.

The X-15 first flew on 8 June 1959 on a glide flight. It was dropped from under the wing of a specially modified B-52 "mother ship." The first powered flight took place on 17 September. Once the X-15 fell clear of the B-52, pilot Scott Crossfield ignited the rocket engine and flew to a relatively pokey Mach .79. On future flights the X-15 flew many times the speed of sound. The X-15 continued flying until 24 October 1968. In all, the program's three aircraft made a total of 199 flights, establishing many records.

One of the storied pilots of the X-15 program was Joe Walker. Through 25 flights behind the controls of the X-15, Walker had many famous moments. He reached 4,104 mph (Mach 5.92) during Flight 59 on 27 June 1962. He also made three X-15 flights into suborbital space, 62 miles. The first was Flight 90 on 19 July 1963 to 66 miles in altitude, and the second, Flight 91 on 22 August 1963 at 67 miles. He then flew more, setting an unofficial world altitude record of 354,200 feet, or 67.08 miles, on 22 August 1963. This marked the highest altitude ever flown in the X-15.

The program's principal purposes included 1) verifying existing theory and wind tunnel techniques about high-speed flight, 2) studying aircraft structures under high (1,200 degrees Fahrenheit) heating, 3) investigating stability and control problems in flight and reentry, and 4) learning the biomedical effects of both weightless and high-g flight. It achieved all of these goals and more. The X-15 actually achieved Mach 6.7, an altitude of 354,200 feet, a skin temperature of 1,350 degrees Fahrenheit, and dynamic pressures over 2,200 pounds per square foot.

After the program achieved its original research goals, moreover, the X-15 proved useful as a high-altitude hypersonic testbed for 46 follow-on experiments. For approximately the last six years of the program, the X-15 supported various types of technology development programs that required high-speed flight. Among other things, it carried micrometeorite collection pods and ablative heat shield samples for Project Apollo and various other experiments.

The X-15 is widely considered the most successful experimental aircraft ever built. Two of the three X-15s—one crashed in 1967 with the loss of the pilot, U.S. Air Force Major Michael J. Adams—remain in museums. The first X-15 is in the National Air and Space Museum in Washington, DC, and the other is in the United States Air Force Museum in Dayton, Ohio. The program yielded over 765 research reports using data from its 199 flights over almost a decade.

The NACA and the National Unitary Wind Tunnel Plan

The X-15 flight research program only achieved reality because of the groundwork laid through the building of several new high-speed wind tunnels immediately after World War II. The NACA and the Air Force championed the National Unitary Wind Tunnel Act of 1949 to build new supersonic test facilities, to upgrade other capabilities, and to support selected initiatives at educational institutions. The NACA push began in April 1945 with a letter to the committee's director of research, George W. Lewis, from Bruce Ayer, an engineer at the Aircraft Engine Research Laboratory (AERL) in Cleveland, Ohio. Ayer suggested that the advent of jet propulsion ensured that research problems for the foreseeable future would emphasize high-speed flight. The NACA needed wind tunnels capable of operating in this flight regime, far beyond the capacity of existing facilities.

Ayer received a polite and noncommittal response from Lewis, but this changed when engineers viewed the facilities Germany had built during World War II. In a 7 November 1945 memorandum to NACA headquarters, AERL director Edward Sharp recommended that "the Committee should at once take steps to preempt this field of high-speed research and an aggressive and vigorous policy should be adopted in the interest of keeping America first in scientific development along these lines."[8] Sharp urged the creation of new supersonic research capabilities under NACA auspices.

With the support of the Department of Defense, the National Unitary Wind Tunnel Act of 1949 as implemented by the NACA and by the U.S. Air Force (established as a separate branch of the U.S. military in the National Security Act of 1947) included five wind tunnel complexes, one each at the three NACA Laboratories and two wind tunnels plus an engine test facility at what would eventually become known as the Air Force's Arnold Engineering Development Center (AEDC) in Tennessee.

The NACA committed to the construction of five supersonic wind tunnels located at its various research laboratories. At Langley in Hampton, Virginia, a 9-inch supersonic tunnel was operating, in which much of the pioneering research on swept-wing drag reduction had been performed. Langley also committed to designing and building a 4- by 4-foot supersonic research wind tunnel. This tunnel would become operational in 1948 following installation of a 45,000-horsepower drive system. At Ames in the Bay Area of California, two supersonic research wind tunnels were constructed. These included the 1- by 3-foot Supersonic Wind Tunnel (SWT) that operated to a maximum test section airspeed of Mach 2.2. A larger 6- by 6-foot supersonic research tunnel was also constructed at Ames. For purposes of flow visualization, it also contained a 50-inch Schlieren window system. Finally, at the Aircraft Engine Propulsion Laboratory (renamed the Lewis Flight Propulsion Laboratory in 1948), the NACA built in 1949 a large 8- by 6-foot transonic wind tunnel with the capability to operate at test section airspeeds from Mach 0.4 to 2.0 and ability to test aircraft power plants. This wind tunnel was an open-circuit tunnel where the air was vented to the atmosphere in order to dispose of engine combustion fumes.

Through the design of these supersonic wind tunnels, NACA engineers perfected their understanding of the differences between supersonic and subsonic aerodynamics. Lessons learned by NACA engineers in the operation of these five supersonic research wind tunnels at the three NACA sites laid the groundwork for that organization's future successes in designing and building modern aircraft and eventually space vehicles.

Making the Jet Engine Efficient (and More Powerful)

While the NACA missed the opportunity to pioneer the jet engine, in the period after World War II engineers largely at the Aircraft Engine Research Laboratory in Cleveland transformed aviation with their powerful, efficient, and safe jet engines. The success of jet aircraft in both Germany and Great Britain in World War II spurred American efforts to catch up to this technology. While the NACA had failed to develop the most revolutionary technology since the Wright brothers, its leaders were intent on making the technology better and exploiting it in every way possible. The Aircraft Engine Research Laboratory, now Glenn Research Center at Lewis Field near Cleveland, Ohio, forwarded a report in December 1945 entitled "Survey of Fundamental Problems Requiring Research" that recommended the expansion of research on the technologies of turbojets, ramjets, and rockets.

The report concluded: "The simultaneous development of aerodynamic shapes for high-speed flight, and the use of jet-reaction power systems has suddenly placed the aeronautical engineer in position to attain supersonic speeds, but as yet only the outer fringes of research on this mode of transportation have been touched."[9] The fundamental technology that the NACA pioneered was the axial flow compressor, a jet in which the air flows parallel to the axis of rotation, is accelerated, and creates greater thrust. The first jets were powered by centrifugal compressors without additional acceleration; these systems

Figure 4-3. This 1946 test of an I-40 Ramjet engine at the NACA's Flight Propulsion Laboratory in Cleveland measured the exhaust gases being discharged from a special burner. Engineers record the test with a motion picture camera. (NASA, GRC-1946-C-16086)

were inefficient and underpowered for anything but the lightest fighter jets. What was needed was axial flow compressors, but the technologies were not well known and most of the baseline knowledge was limited to a few empirical tests over a limited aerodynamic regime. NACA researchers would change that in the years that followed.

As authors George E. Smith and David A. Mindell noted, axial flow compression was attained by "stacking a sequence of these airfoil profiles radially on top of one another as if the air flows through the blade row in a modular series of radially stacked two-dimensional blade passages."[10] The expansion of this approach required a detailed, lengthy, and expensive research agenda only able to be carried out by a government laboratory. The contribution was the three-volume "Compressor Bible," issued in final form in 1956 after a decade of research. This study was based on a painstaking empirical research effort that included wind tunnel research and flight research, as well as theoretical studies.

The knowledge gained through the NACA's research filtered out of the agency through the usual means of technical reports and personal contacts as well as with the departure from the NACA of several key researchers who moved to General Electric (GE) and developed axial-flow compressor engines, especially turbofans, into the mainstay of American jet technology. Langley's Jack Erwin and Lewis's John Klapproth, Karl Kovach, and Lin Wright departed for GE in 1955 and 1956. These engineers proved instrumental in designing the pathbreaking large axial-flow turbofan, the J-79 military jet engine powering the B-58 Hustler, Lockheed F-104 Starfighter, McDonnell Douglas F-4 Phantom II, and North American A-5 Vigilante, oriented toward performance as high as Mach 2. The commercial equivalent, the CJ805, powered the Convair 880 and 990 airliners. Under the leadership of John Blanton at GE, this team successfully developed a powerful family of engines that found use across a broad spectrum. The NACA's contribution included not only basic research but design expertise. The role of Lin Wright proved especially critical; he was an African American engineer from Wayne State University in Detroit, Michigan, who worked for a decade at Lewis, and then transitioned to GE just as the American civil rights movement was emerging as a force in national politics. Far from an activist, Wright contributed most to that cause through his excellence as an engineer on the cutting edge of aeronautical research and development.

The NACA and Rocket Research

During the latter part of World War II, leaders of the NACA had become interested in the possibilities of high-speed guided missiles and the future of spaceflight. It created the Pilotless Aircraft Research Division (PARD), under the leadership of a young and promising engineer at Langley, Robert R. Gilruth.

Gilruth, perhaps more than any other NACA official, served as the godfather of human spaceflight in the United States. After his central role in PARD, he went on to lead the Space Task Group for NASA that accomplished Project Mercury and then served as director of the Manned Spacecraft Center—renamed the Johnson Space Center in 1973—which had suzerainty over Gemini and Apollo. His organization recruited, trained, and oversaw the astronauts and the human spaceflight program throughout the heroic age of spaceflight. Yet his name is much less well known than many others associated with these projects. He was a contemporary on a par with Wernher von Braun and a host of other NASA officials, and he certainly contributed as much to human spaceflight as any of them.

Gilruth was representative of the engineering entrepreneur, a developer and manager of complex technological and organizational systems, accomplishing remarkably difficult tasks through excellent oversight of the technical, fiscal, cultural, and social reins of the effort. Johnson Space Center Director George W. S. Abbey appropriately commented at the time of Gilruth's death in 2000: "Robert Gilruth was a true pioneer in every sense of the word and the father of human spaceflight. His vision, energy and dedication helped define the American space program. His leadership turned the fledgling Manned Spacecraft Center into what it is today, the leader in humanity's exploration of outer space."[11]

Gilruth established Wallops Island on the Eastern Shore as a test-launching facility under the control of Langley on 4 July 1945. From this site, between 1947 and 1949, they launched at least 386 models, leading to the publication of the NACA's first technical report on rocketry, "Aerodynamic Problems of Guided Missiles," in 1947. From this, Gilruth and the PARD filled in the gaps in the knowledge of spaceflight. As Langley Research Center historian James R. Hansen writes: "the early years of the rocket-model program at Wallops (1945–1951) showed that Langley was able to tackle an enormously difficult new field of research with innovation and imagination."[12]

Gilruth served as an active promoter of the idea of human spaceflight within the NACA and helped to engineer the creation of an interagency board to review "research on space flight and associated problems" toward that end.[13] "When you think about putting a man up there, that's a different thing," he recalled. "There are a lot of things you can do with men up in orbit."[14] This led to concerted efforts to develop the technology necessary to make it a reality. In 1952, for example, PARD started the development of multistage, hypersonic, solid-fuel rocket vehicles. These vehicles were used primarily in aerodynamic heating

Figure 4-4. It might not have been an impressive feat compared to military rocket development at this time, but this first launch of the NACA's Pilotless Aircraft Research Division (PARD) on 27 June 1945 portended significant research to follow. Through 1958, the PARD launched nearly 400 different types of rockets from Wallops Island, Virginia. The site remains operational to the present. (NASA, EL-2000-00254)

tests at first and were then directed toward a reentry physics research program. On 14 October 1954, the first American four-stage rocket was launched by the PARD, and in August 1956 it launched a five-stage, solid-fuel rocket test vehicle, the world's first, that reached a speed of Mach 15.

These strides in the development of rocket technology positioned the NACA as a quintessential agency in the quest for space, which was becoming important in the 1950s. And it enjoyed renewed attention and funding once the Soviet Union launched the world's first satellite, Sputnik, on 4 October 1957. "I can recall watching the sunlight reflect off of Sputnik as it passed over my home on the Chesapeake Bay in Virginia," Gilruth commented in 1972. "It put a new sense of value and urgency on things we had been doing. When one month later the dog Laika was placed in orbit in Sputnik II, I was sure that the Russians were planning for man-in-space."[15]

It soon became obvious that an early opportunity to launch human spacecraft into orbit would require the development of blunt-body capsules launched on modified multistage intercontinental ballistic missile (ICBMs). Robert Gilruth recalled these decisions:

> Because of its great simplicity, the non-lifting, ballistic-type of vehicle was the front runner of all proposed manned satellites, in my judgment. There were many variations of this and other concepts under study by both government and industry groups at that time. The choice involved considerations of weight, launch vehicle, reentry body design, and to be honest, gut feelings. Some people felt that man-in-space was only a stunt. The ballistic approach, in particular, was under fire since it was such a radical departure from the airplane. It was called by its opponents "the man in the can," and the pilot was termed only a "medical specimen." Others thought it was just too undignified a way to fly.[16]

While initially criticized as an inelegant, impractical solution to the challenge of human spaceflight, the ballistic concept gained momentum from NACA engineers, led by Maxime A. Faget. At a meeting on human spaceflight held at Ames on 18 March 1958, the ballistic approach gained official support. By April 1958, the NACA had completed several studies relating to human spacecraft, finding that they could build in the near term a ballistic capsule of approximately 2,000 pounds and sufficient volume for a passenger modeled on the technology being developed for nuclear warheads.

In August 1958, the NACA developed preliminary specifications that then went to industry, especially the McDonnell Aircraft Corporation, for a ballistic capsule. Gilruth emphasized the simplicity if not the elegance of a ballistic capsule for the effort:

> The ballistic reentry vehicle also has certain attractive operational aspects which should be mentioned. Since it follows a ballistic path there is a minimum requirement for autopilot, guidance, or control equipment. This condition not only results in a weight saving but also eliminates the hazard of malfunction. In order to return to the earth from orbit, the ballistic reentry vehicle must properly perform only one maneuver. This maneuver is the initiation of reentry by firing the retrograde rocket. Once this maneuver is completed (and from a safety standpoint alone it need not be done with a great deal of precision), the vehicle will enter the earth's atmosphere. The success of the reentry is then dependent only upon the inherent stability and structural integrity of the vehicle. These are things of a passive nature and should be thoroughly checked out prior to the first man-carrying flight. Against these advantages the disadvantage of large area landing by parachute with no corrective control during the reentry must be considered.[17]

The Mercury spacecraft that flew in 1961–63 emerged from these early conceptual studies by the NACA.

World-Class Aeronautical Research and Development

As a measure of the success of the NACA in aerospace research in the post–World War II era, the National Aeronautic Association (NAA) awarded the prestigious Robert A. Collier trophies to the agency four times between 1946 and 1954. Established in 1911, the Collier Trophy was given annually "for the greatest achievement in aeronautics or astronautics in America, with respect to improving the performance, efficiency, and safety of air or space vehicles, the value of which has been thoroughly demonstrated by actual use during the preceding year." A garish Art Deco design with a sculpture evoking human flight, the Collier Trophy has been overseen by the National Aeronautic Association since its inception, placed on permanent display at the Smithsonian Institution, and in its earliest era awarded in a ceremony presided over by the President of the United States. The NACA first received the Collier Trophy in 1929 for the development of low-drag cowling for radial air-cooled aircraft engines, but nothing thereafter received this status until 1947. Then, in the space of less than a decade, the NACA received four more Collier Trophies for its research.

In 1946, NACA researcher Lewis A. Rodert of Ames Aeronautical Laboratory in the San Francisco Bay area of California received the trophy for the development of an efficient wing-deicing system, a persistent problem on aircraft wings since the beginning of the air age. Rodert led a team for more than a decade building an effective deicing system for aircraft. Incrementally building a knowledge base that led from meteorological studies of icing conditions to wind tunnel research, Rodert modified a Lockheed A-12 initially and later a Douglas C-46 to demonstrate that icy conditions need not ground aircraft, a frequent problem that led to flight cancellations. Indeed, subsequent research has continued to refine solutions to this knotty problem. Rodert's solution involved vectoring engine exhaust to various parts of the aircraft where icing problems occurred, affixing heat exchangers, pioneering chemicals to prevent ice from forming on wings, and placing inflatable "boots" on the leading edges of wings that could rupture the ice forming there. Rodert's highly important but far from glamorous research demonstrated the realization of the NACA's fundamental mission "to supervise and direct the scientific study of the problems of flight with a view to their practical solution."

If the first postwar Collier Trophy in 1946 served as a model of long-term, grindingly mundane aeronautical research, the second postwar award in 1947 for supersonic flight research served as a model of cooperative efforts between the NACA and the military services in a highly dramatic arena. The agency's John Stack, as well as the Army's Chuck Yeager and Bell Aircraft's Larry Bell, received the Collier Trophy for the work of the X-1 supersonic flight research project. The citation for Stack read: "for pioneering research to determine the physical laws affecting supersonic flight and for his conception of transonic research airplanes."[18] In this sense, as aerodynamicist John D. Anderson has noted: "Stack was performing as an *engineering scientist* in this activity, neither a pure scientist nor a pure engineer. The NACA had provided all the elements that allowed this engineering science contribution to occur."[19]

The third NACA postwar Collier Trophy, in 1951, also went to John Stack for the development of the slotted-throat wind tunnel. Once again, this technology served the cause of higher, faster, and farther flight at a critical time in the development of aviation. The Cold War was just emerging as a major force, and the technology of nuclear deterrence required aerospace capabilities not yet in existence. Langley theoretician Ray H. Wright determined that the best type of wind tunnel for operating from the subsonic through the transonic and into the supersonic realms involved placing slots in the test section throat. This design allowed effective and evenly formed airflow in the Mach 1 realm, approximately 761 mph at sea level. The smoothing of shock waves—also called the boundary layer—enabled critical research leading to supersonic fighters used by the American military. Stack oversaw efforts to retrofit both Langley's 8-Foot High Speed Tunnel and its 16-Foot High Speed Tunnel with a new slotted throat design. He successfully operated to the Mach 1.2 region and in the process pushed back significantly the high-speed frontier. As aerodynamicist Laurence Loftin concluded, "the newly converted tunnels were valuable," they "provided a new dimension in transonic testing."[20]

Finally, the last pre-NASA Collier Trophy to be awarded to the NACA came in 1954 in honor of the work of Richard Whittle for the "area rule": a groundbreaking design concept that has governed the design of high-performance jets ever since. Whittle's transonic area rule emerged from research using Langley's slotted test section of the 8-Foot HST. He found that an increase in drag due to shock wave formation could be mitigated with an elongated streamlined body wider at the forward edge and gradually tapering to a narrower aft section. Refining the concept into a useful equation, Whittle applied it with exceptional results in the design of the Convair F-102 interceptor aircraft. The same was true for Grumman's first supersonic carrier-based fighter, the F9F/F-11F Tiger. The area rule has been incorporated into every high-performance aircraft since that time, most visibly with the Boeing-747 hump-back design of the 1960s. Little wonder Richard Whittle received the Collier Trophy for this innovation in 1954. According to the citation for the award, a "powerful, simple, and useful

Figure 4-5. In April 1955, NACA engineer Richard Whitcomb examines a model designed according to principles of his transonic area rule in the Langley 8-foot High-Speed Wind Tunnel. (NASA, LRC-1954-B701_P-89119)

method of reducing greatly the sharp increase in wing drag heretofore associated with transonic flight, and which constituted a major factor requiring great reserves of power to attain supersonic speeds."

During this immediate postwar period, the NACA's research program partnered with industry, military, and commercial interests to create world-class knowledge about the problems of flight and realize their practical solutions. It built on its traditional strengths in aerodynamics research and extended it into high-speed flight and rocketry. Little did Hugh Dryden, NACA Director of Research since 1948, and other officials realize that the landscape was about to change. The NACA would undergo a major transformation in 1958 in response to one of the most significant events in the history of flight, the Sputnik crisis, and the resultant belief that the United States must undertake a campaign to "catch up" to the Soviet Union in space.

CHAPTER 5

Becoming NASA

"It's up," Walter Sullivan, a reporter with the *New York Times*, told Richard Porter, a member of the International Geophysical Year (IGY) committee after arriving at the cocktail party on the evening of 4 October 1957. Porter's ruddy face flushed even more as he heard this news; he knew exactly what it meant. The Soviet scientists at the meeting had been hinting that they may have some news before the end of the scientific gathering in Washington, D.C. Porter glided through the gaggles of scientists, politicians, journalists, straphangers, and spies in search of Lloyd Berkner, the official American delegate to the Comité Spécial de l'Année Géophysique Internationale (CSAGI), which coordinated IGY planning.[1]

When told the news, Berkner acted with the characteristic charm of his polished demeanor. Clapping his hands for attention, he asked for silence. "I wish to make an announcement," he declared. "I've just been informed by the *New York Times* that a Russian satellite is in orbit at an elevation of 900 kilometers. I wish to congratulate our Soviet colleagues on their achievement."[2]

Virtually everyone would agree that the launch of Sputnik on 4 October 1957 represented a major episode in the history of the Cold War, the 20th century, and the American century. An extremely specific understanding about this event quickly emerged and has dominated conceptions of the event to the present. Essentially, this understanding relates how the United States was surprised and shocked by the launch of a Soviet orbital satellite and its citizenry registered a crisis of fear. The result, however, proved ultimately quite positive, and in a twist that captures the essence of an overarching American exceptionalism, the nation rose to the occasion by restructuring its space activities, establishing NASA, and reaching the Moon by 1969.

To a very real extent, NASA's creation and initial modest space exploration agenda was the product of the interchange between Eisenhower's vision of limited government and a loosely defined set of interest groups that pressed for aggressive but perhaps ill-considered action in the immediate post-Sputnik era. This cadre of interests sought to create a powerful government bureaucracy, perhaps even a cabinet-level department, to carry out a far-reaching and exceptionally expensive agenda in space. So successful were these groups in promoting their image of space exploration that the Eisenhower administration had to compromise its limited agenda, and after Kennedy entered the White House in 1961 space advocates moved to increase the size, scope, and budget of NASA.

Sputnik Night

The story of the IGY, Sputnik, and the creation of NASA are well-known elements of the larger story of the beginnings of the Space Age. This story begins with the rise of the U.S. space program in response to the pressures of national security during the Cold War with the Soviet Union. From the latter 1940s, several government agencies, including the NACA, had pursued research in rocketry and upper atmospheric sciences as a means of assuring American leadership in science and technology and for the purposes of national security. This space effort received a huge boost in 1952 when the International Council of Scientific Unions established a committee to arrange an International Geophysical Year for the period 1 July 1957 to 31 December 1958, with the inclusion of an orbital satellite objective as a part of the effort.

The Naval Research Laboratory's Project Vanguard was chosen on 9 September 1955 to support the IGY effort, in part because it did not interfere with high-priority ballistic missile development programs—it used the non-ballistic missile Viking rocket as its basis—while an Army proposal to use the Wernher von Braun–developed ballistic missile as the launch vehicle waited in the wings. Project Vanguard enjoyed exceptional publicity throughout the second half of 1955 and all of 1956, but the technological demands upon the program were too great and the funding levels too small to foster much success.

Beginning on Monday, 30 September, the international scientific organization CSAGI had a conference at the U.S. National Academy of Sciences in Washington on rocket and satellite research for the IGY. Scientists from the United States, the Soviet Union, and five other nations met to discuss their individual plans and scientific data and findings. Hints from the Soviets at the meeting, however, threw the conference into a tizzy of speculation. Several Soviet officials had intimated that they could probably launch their scientific satellite within weeks instead of months, as the public schedule said. Senior scientist Sergei M. Poloskov's offhand remark on the conference's first day that the Soviet Union was "on the eve of the first artificial earth satellite" proved more than boastful rhetoric.[3]

The inner turmoil of the Sputnik crisis came in part because American efforts to launch a satellite, at least to be first, had failed. Some have suggested that this represented "the shock of the century," but that shock only slowly reverberated through the American public in the days that followed. Most Americans seemed to recognize that the satellite did not pose a threat to the United States and congratulations were in order for the Soviet Union.

Instead, most Americans embraced the dawn of the Space Age as a symbol of progress and a better future both on Earth and beyond. Raised on visions of human colonies on the Moon and Mars, great starships plying galactic oceans; and prospects of a bright, limitless future beyond a confining, overcrowded, and resource-depleted Earth brought to the public by the likes of media magnate Walt Disney and German rocketeer Wernher von Braun, a generation of Americans embraced a promising future in space. Taught in the early 1950s that spaceflight loomed just on the cusp of reality, they now saw that perception come true. For one, it thrilled 14-year-old Homer Hickam as he watched "the bright little ball, moving majestically across the narrow star field between the ridgelines" of his home in Coalwood, West Virginia. It inspired him, and many like him, to devote their lives to the quest for space.[4]

In fact, the best evidence suggests that excitement about prospects for the future dominated the thinking of the American public immediately after the Sputnik launch. Three days after its launch, social anthropologists Margaret Mead and Rhoda Metraux began collecting data gauging American responses to Sputnik. They asked colleagues and friends around the country to conduct surveys asking three open-ended questions among divergent age, gender, race, economic, and social groups of all:

1. What do you think about the satellite?
2. How do you explain Russia's getting their satellite up first?
3. What do you think we can do to make up for it?

Mead and Metraux collected 2,991 adult responses until 18 October, and these responses suggest the need for a revision to the master narrative since neither shock nor awe was present. An exceptionally small number said that the Soviet launch of Sputnik was an unexpected event; an even smaller number registered no knowledge of the launch. Of those who had little or no knowledge, the response of one 22-year-old white female from Austin, Texas, was characteristic: "It was a surprise to hear that the satellite was launched successfully.… I was skeptical that such a project would ever materialize. Now that it has, it shows that science is still progressing."[5] Another respondent, a 40-year-old white male from Louisville, said it this way: "It's been a scientific possibility for some time…. Russia had said she would launch it, so it did not come as a surprise."[6] While few interviewees chose to call Sputnik a surprise, most knew little about the space efforts in either the United States or the Soviet Union. As one investigator summarized in a report on this study, "[It] seems that most informants in the 'Emergency Survey,' whether or not they possessed prior knowledge about artificial satellites, had taken the news of Sputnik in stride and developed a logical, rather than emotional, approach to the topic by the time they were interviewed."[7]

This assessment squares with a more scientific study of the Sputnik response. As a government study reported in October 1958:

> Interpretations of the Sputnik's significance likewise show that public concern was not great. Gallup found that only 50 percent of a sample taken in Washington and Chicago regarded the Sputnik as a blow to our prestige. Sixty percent said that we, not the Russians, would make the next great "scientific" (actually technological) advance. A poll by the *Minneapolis Star and Tribune* found that 65 percent of a sample in that State thought we could send up a satellite within 30 days following the Russian success, a statistic which included 56 percent of the college-educated persons asked. In the sample of the Opinion Research Corporation, 13 percent believed that we had fallen behind dangerously, 36 percent that we were behind but would catch up, and 46 percent said that we were still at least abreast of Russia.[8]

There is good reason to believe that the Democrats used Sputnik to embarrass President Eisenhower and the Republicans in Congress. George Reedy, a Democratic strategist, wrote to Senator Lyndon B. Johnson (LBJ) on 17 October 1957 about how to do so: "the issue is one which, if properly handled, would blast the Republicans out of the water, unify the Democratic Party, and elect you President." He suggested that "you should plan to plunge heavily into this one. As long as you stick to the facts and do not get partisan, you will not be out on any limb." Reedy added that to use such an issue to wrest power from the Republicans, LBJ and his caucus in Congress would need to establish the legitimacy, breadth, and dynamism of the Sputnik issue. He noted: "Folks will start getting together in the evening over a case of beer and some field glasses watching for Sputnik and ignoring television. And when two or three of the satellites get into the ionosphere, what is now curiosity may turn into something close to panic."[9]

Using every tool at their disposal, LBJ and his associates worked to maximize the Sputnik launch for their political purposes. Speaking for many Americans, he remarked in two speeches in Texas in the fall of 1957 that the "Soviets have beaten us at our own game—daring, scientific advances in the atomic age." Since those Cold War rivals had already established a foothold in space, Johnson proposed to "take a long careful look" at why the U.S. space program was trailing that of the Soviet Union.[10] He led a broad review of American defense and space programs in the wake of the Sputnik crisis. Eventually, the public may have gotten very afraid of the ramifications of the satellite, but not immediately.

Creating a Unified Space Program

Two major concerns immediately emerged as the American public came to grips with the Soviet satellite. First, reviews ascertained the status of existing space-related activities and found them wanting. The Eisenhower administration, however, took steps to assure that progress sped up, and the result was the launch of Explorer 1 on 31 January 1958.

Figure 5-1. This iconic image from the launch of Explorer 1 on 31 January 1958 was taken at a press conference at the National Academy of Sciences building in Washington, DC. Holding up a backup of Explorer 1 are (L–R) William Pickering, director of the Jet Propulsion Laboratory and lead on the science effort for Explorer 1; James Van Allen, scientific principal investigator for the mission; and Wernher von Braun, technical director of the Army Ballistic Missile Agency that built and launched the Redstone rocket that placed Explorer 1 in orbit. (NASA, 5663627)

Second, governmental inquiries assessed the nature, scope, and organization of the nation's long-term efforts in space. The findings were bleak, and as a direct result, on 6 February 1958, the Senate voted to create a Special Committee on Space and Aeronautics whose charter was to frame legislation for a permanent space agency. The House of Representatives soon followed suit. With Congress leading the way and fueled by a crisis atmosphere in Washington following the Sputnik episode, it was obvious that some government organization to direct American space efforts would emerge before the end of the year.

The principal questions concerning any new space agency in the first half of 1958 revolved around whether it should be civilian or military in orientation and organization, whether it should be an existing or newly created entity, and how aggressive it should be in exploring space. On 4 February 1958, the President asked his science advisor, James R. Killian, to convene the President's Science Advisory Committee (PSAC), established in the wake of Sputnik, to come up with a plan. A month later, Killian came forward with a proposal that placed all non-military efforts relative to space exploration under a strengthened and renamed NACA.

President Eisenhower accepted the PSAC's recommendations and had members of his administration draft legislation to expand the NACA into NASA. It set forth a broad mission for the Agency to "plan, direct, and conduct aeronautical and space activities"; to involve the nation's scientific community in these activities; and to disseminate widely information about these activities.[11]

Eisenhower opposed one aspect of this legislation, a Space Council that he feared would become a powerful new organization that would require too much of his attention. Eisenhower and Johnson met on 7 July 1958 to discuss this problem. They compromised; Eisenhower allowed the Space Council with the President chairing it, thereby setting its agenda and channeling its efforts. The National Aeronautics and Space Act of 1958 was passed by Congress. Eisenhower signed it into law on 29 July 1958, and the new organization started functioning on 1 October.

Constructing NASA

The 170 employees of the new space organization gathered in the courtyard of the Dolley Madison House near the White House in downtown Washington on 1 October 1958 to listen to the newly appointed NASA Administrator, T. Keith Glennan, announce the bold prospects being considered for space exploration. Glennan, fresh from the presidency of the Case Institute of Technology in Cleveland, Ohio, presided over a NASA that had absorbed the NACA intact with its 8,000 employees and an annual budget of $100 million. It consisted of a small headquarters staff in Washington that directed operations along with three major research laboratories—Langley (Hampton, Virginia, 1918), Ames (Bay Area, California, 1940), and Lewis (Cleveland, Ohio, 1941)—and two small test facilities, one for high-speed flight research at Muroc Dry Lake in the high desert of California and one for sounding rockets at Wallops Island, Virginia. The scientists and engineers that came into NASA from the NACA brought a strong sense of technical competence, a commitment to collegial in-house research conducive to engineering innovation, and a definite apolitical perspective.

Within a short time after NASA's formal establishment, several organizations involved in space exploration projects from other federal organizations were incorporated into NASA. One of the important ingredients was the 150 personnel associated with Project Vanguard at the Naval Research Laboratory located along the Potomac River just outside of Washington. Officially becoming a part of NASA on 16 November 1958, this laboratory remained under the operational control of the Navy until 1960, when it was transferred from Navy facilities to a newly established NASA installation, the Goddard Space Flight Center, in Greenbelt, Maryland. Those who had been associated with the Naval Research Laboratory brought a similar level of scientific competence and emphasis on in-house research and technical mastery that had been the hallmark of the NACA elements.

In addition to the Project Vanguard personnel and resources, NASA quickly gained several disparate satellite programs, two lunar probes, and the important research effort to develop a million-pound-thrust, single-chamber rocket engine from the Air Force and DOD's Advanced Research Projects Agency. In December 1958, NASA also acquired control of the Jet Propulsion Laboratory, a contractor facility operated by the California Institute of Technology (Caltech) in Pasadena, California. Coming from the Army, this oddly named institution had been specializing in the development of weaponry since World War II.

During this period of rapid expansion, Glennan also asked for the transfer to NASA of part of the Army Ballistic Missile Agency (ABMA) at the Redstone Arsenal, located at Huntsville, Alabama, and presided over by one of the nation's foremost space advocates, German postwar immigrant Wernher von Braun. The Army dug in its heels, however, and refused to give up the jewel in the crown of its space vision. Von Braun's German rocket team, as it was called, numbered only about 100 people, but it was firmly in control of the 4,500-person installation at Huntsville, and it was the Army's centerpiece in an interservice struggle for the space mission. The Army pinned high hopes on ABMA's most important project, the development of a rocket that could deliver 1.5 million pounds of thrust in the first stage, eventually named the Saturn. The Saturn would without question establish the Army's leadership in the development of space technology.

The Army resisted NASA's overtures for 18 months. During the summer of 1959, however, congressional criticism forced DOD to reevaluate the Army's Saturn program. The Army, within its assigned military mission, had no business developing this super space booster. If there was a military use, which was problematic, it clearly rested within the Air Force's mission rather than the Army's. NASA exploited this criticism and suggested that it definitely had a use for the Saturn launch vehicle, so a transfer of all personnel and resources associated with the project to the space agency would be appropriate. Additionally, Glennan also argued that transfer of the Saturn to NASA would avoid interservice rivalries, which were always tense, since DOD would not have to choose between the Army and the Air Force. Accordingly, on 1 July 1960, the ABMA's shift from the Army to NASA with all personnel and resources intact was completed. It was renamed the George C. Marshall Space Flight Center in honor of the American army officer and secretary of defense who had helped win World War II and then rebuild Europe. This rocket team brought to NASA a strong sense of technical competence, a keen commitment to the goal as defined by von Braun, and an especially hardy group identity.

By mid-1960, NASA had gained primacy in the federal government for the execution of all space activities except DOD-controlled reconnaissance satellites, ballistic missiles, and a few other projects, most of which were still in the study stage. These military missions were still considerable, however, and accounted for over half of the federal budget spent on the space effort at the time. The clear mandate from the Eisenhower administration, it should be emphasized, was that NASA's space efforts would be both non-military in character and highly visible to the public. This would serve two distinct but necessary purposes. First, NASA's projects were clearly Cold War propaganda weapons that national leaders wanted to use to sway world opinion about the relative merits of democracy versus the communism of the Soviet Union. The rivalry was not friendly, and the stakes were potentially quite high, but at least this competition had the virtue of not being military in disposition. It was not, after all, an arms race, and the likelihood of any aspect of it leading to war and potentially to nuclear destruction was slim. Second, NASA's civilian effort served as an excellent smokescreen for DOD's military space activities, especially for reconnaissance missions. NASA's civilian mission, therefore, dovetailed nicely into Cold War rivalries and priorities in national defense.

America's Human Spaceflight Agenda

Also in the latter 1950s, NASA began plans for the orbiting of an American around Earth. This proved an especially attractive idea since the Soviet Union had already a large measure of prestige in their satellite programs. Human spaceflight, therefore, became the next arena for competition between the United States and the Soviet Union in the Cold War. All the uniformed services got into the act, and even before the creation of NASA they had developed plans for sending an American into space.

The Air Force project, with the unlikely name of Man in Space Soonest (MISS), advocated a four-part plan to land humans on the Moon by the end of 1965 using existing military boosters at the bargain basement price of $1.5 billion. Even more far-fetched was the Navy's proposal to orbit a novel spacecraft, a cylinder with spherical ends that would telescope into a delta-wing, inflated glider with a rigid nose section. The Manned Earth Reconnaissance (MER) program was an innovative idea that had little chance of success because of its emphasis on new hardware and entirely unexamined techniques, and it was quickly derailed. The Army's entry into the human spaceflight sweepstakes was devised at ABMA by Wernher von Braun and his rocket team. Much simpler and less ambitious than the Air Force and Navy plans, Project Adam called for the use of a modified Redstone booster to launch a pilot in a capsule along a steep ballistic, suborbital trajectory. The capsule would reach an altitude of about 150 miles before splashing down by parachute in the Atlantic missile range east of Cape Canaveral, Florida, where von Braun had established ABMA's launch facilities. In spite of the seriousness with which the Army put forth this plan, many agreed with Dr. Hugh L. Dryden, the NACA's Director of Research, that it had "about the same technical value as the circus stunt of shooting the young lady from the gun."[12]

The front-runner throughout these deliberations was the Air Force's MISS program. Soon after New Year's Day 1958, Air Force officials asked the NACA to collaborate in this effort on a human spaceflight effort, but with the NACA as a decidedly junior partner. NACA Director Hugh Dryden agreed but had no intention of remaining a junior partner. He commented: "Although it is clear that both the National Aeronautics and Space Administration and the Department of Defense should cooperate in the conduct of the program, I feel that the responsibility for and the direction of the program should rest with NASA."[13] Dryden asked the President to adjudicate the issue.

Eisenhower did just that when he assigned the U.S. Air Force's human spaceflight mission to NASA in August 1958. Thereafter, the MISS program was folded into what became Project Mercury. The *coup de grâce* to each of these programs came with the actual creation of NASA and its presidentially approved assignment of putting an American in space. A few NACA engineers under the leadership of Dr. Robert R. Gilruth at Langley Aeronautical Laboratory had initiated work on the possibility of a piloted spacecraft in the spring of 1958, and just days after NASA was officially activated, they proposed Project Mercury to Administrator Glennan.

NASA adopted a two-phased project: 1) Redstone missiles would be used to send humans on suborbital ballistic flights 2) and Atlas boosters would launch an occupied capsule into orbit. In all, the project called for six piloted flights. Emphasizing the use of existing technology, relative simplicity, and a progressive and logical testing program, the plan realistically aimed toward the objective of putting a human in orbit within two years. NASA Administrator T. Keith Glennan gave his blessing and established a Space Task Group under Gilruth to supervise the Mercury program. This group in 1962 moved to a new research installation, the Manned Spacecraft Center (renamed the Lyndon B. Johnson Space Center in 1973), near Houston, Texas. The decision to locate the Center in Houston, it should be mentioned, apparently resulted from the influence of House Speaker Albert Thomas, who represented that district in Congress.

During the months following approval of Project Mercury, the Space Task Group energetically pursued the development of the hardware and support structure to handle the program. The Space Task Group focused on the core challenge in Project Mercury, investigating the effects of weightlessness and other conditions on the human form or, as the charter for the project read, "to investigate the capabilities of man in this environment."[14] Dr. Maxime A. Faget was the chief designer of the Mercury spacecraft, a compact vehicle capable of sustaining a single person in orbit for about 24 hours.

Managing Project Mercury

To achieve its newly assigned human spaceflight mission, NASA initially applied principles of management learned during nearly 50 years of experience in the NACA, from which the majority of those making up NASA in its first years were drawn. Just six days after NASA was established on 1 October 1958, Administrator T. Keith Glennan approved plans for Mercury. On 8 October, he gave Gilruth authority to proceed. Thirty-five key staff members from the Langley Research Center, some of whom had been working on a military human spaceflight effort, were transferred to the new Space Task Group, as were 10 others from the Lewis Research Center, near Cleveland, Ohio. These 45 engineers formed the nucleus of the more than 1,000-person workforce that eventually took part in Project Mercury. As Glennan wrote in his diary,

Figure 5-2. NASA technicians assemble Mercury Little Joe boilerplate capsules designed to launch monkeys. The bulky test equipment and a less-than-sterile environment are a far cry from the clean-room conditions that emerged in Project Apollo. (NASA, LRC-1959-B701_P-04947)

"The philosophy of the project was to use known technologies, extending the state of the art as little as necessary, and relying on the unproven Atlas. As one looks back, it is clear that we did not know much about what we were doing. Yet the Mercury program was one of the best organized and managed of any I have been associated with."[15]

Late in 1959, the McDonnell Aircraft Corporation delivered the first Mercury space capsules. The capsule was about 11 feet long and 6 feet wide at the base and conical in shape. Designed to orbit with the astronaut seated facing backward, it would be slowed by a retrorocket pack to allow gravity to bring it back to Earth. The spacecraft came down to an ocean landing braked by parachutes. The astronaut had extraordinarily little room for movement, being placed in an individually fitted contour seat for the duration of the flight. Engineers began integrating the boosters and the spacecraft into a unit that would operate reliably together. This effort was aided by the transfer of ABMA to NASA and the easier ability to tap the expertise of the builders of the Redstone rocket. Additionally, NASA expanded the infrastructure supporting spaceflight operations by establishing ground tracking stations around the globe, a nascent launch and mission control center in Cape Canaveral, Florida, and a complex communications system.

The first Mercury test flight took place on 21 August 1959, when a capsule carrying two rhesus monkeys was launched atop a cluster of Little Joe solid-fuel rockets. Other tests using both Redstone and Atlas boosters and carrying both chimpanzees and astronaut dummies soon followed. For instance, on 31 January 1961, the chimpanzee Ham flew 157 miles into space in a 16-minute, 39-second flight in a Mercury/Redstone combination and was successfully recovered.

Such a small program, imbued with outstanding leadership from Robert Gilruth and staffed by a dedicated team of engineers, succeeded well.

Meet the Mercury Seven

Concurrent with this effort, NASA selected and trained the Mercury astronaut corps. Contrary to a NASA priority that these six astronauts be civilians, President Eisenhower directed that they come from the armed services' test pilot force. NASA had pursued a rigorous process to select the eventual astronauts that became known as the Mercury Seven. The process involved record reviews, biomedical tests, psychological profiles, and a host of interviews. In November 1958, aeromedical consultants working for the Space Task Group at Langley had worked out preliminary procedures for the selection of astronauts to pilot the Mercury spacecraft. They then advertised among military test pilots for candidates for astronaut, including five Marines, 47 Navy aviators, and 58 Air Force pilots.

A grueling selection process began in January 1959. Headed by the Assistant Director of the Space Task Group, Charles J. Donlan, the evaluation committee divided the list of 110 arbitrarily into three groups and issued invitations for the first group of 35 to come to Washington at the beginning of February for

Figure 5-3. The Mercury Seven astronauts in their iconic silver spacesuits, 1959. From left to right, back row, they are Alan Shepard, Virgil "Gus" Grissom, and L. Gordon Cooper; front row, Walter Schirra, Donald "Deke" Slayton, John Glenn, and Scott Carpenter. (NASA, EL-1996-00089)

briefings and interviews. Donlan's team initially planned to select 12 astronauts, but as team member George M. Low reported:

> During the briefings and interviews it became apparent that the final number of pilots should be smaller than the twelve originally planned for. The high rate of interest in the project indicates that few, if any, of the men will drop out during the training program. It would, therefore, not be fair to the men to carry along some who would not be able to participate in the flight program. Consequently, a recommendation has been made to name only six finalists.[16]

By the first of March 1959, 32 pilots had prepared to undergo a rigorous set of physical and mental examinations. They did not know it at the time, but they were asked to serve essentially as specimens for biomedical investigation. Some came to resent it. Each went to the Lovelace Clinic in Albuquerque, New Mexico, where flight surgeon William R. "Randy" Lovelace II concocted a set of individual medical evaluations that stretched the bounds of what was allowed for medical experimentation. In addition, NASA allowed others to subject the prospective astronauts to a broad battery of environmental studies, physical endurance tests, and psychiatric studies at the Aeromedical Laboratory of the Wright Air Development Center, Dayton, Ohio.

NASA unveiled the Mercury astronauts on 9 April 1959, a week before the cherry blossoms bloomed along the tidal basin in Washington, DC. NASA's makeshift headquarters was abuzz with excitement. Employees had turned the largest room of the second floor of the Dolley Madison House facing Lafayette Park near the White House, once a ballroom, into a hastily set-up press briefing room. Inadequate for the task, print and electronic media jammed into the room to see the first astronauts. One end of the room sported a stage complete with curtain, and both NASA officials and the newly chosen astronauts waited behind it for the press conference to begin at 2 p.m. News photographers gathered at the foot of the stage, and journalists of all stripes occupied seats in the gallery. NASA employees brought in more chairs and tried to make the journalists as comfortable as possible in the cramped surroundings.

When the curtain went up, NASA public affairs officer par excellence Walter Bonney announced:

> Ladies and gentlemen, may I have your attention, please. The rules of this briefing are very simple. In about sixty seconds we will give you the announcement that you have been waiting for: the names of the seven volunteers who will become the Mercury astronaut team. Following the distribution of the kit—and this will be done as speedily as possible—those of you who have p.m. deadline problems had better dash for your phones. We will have about a ten- or twelve-minute break during which the gentlemen will be available for picture taking.[17]

Like a dam breaking, a sea of photographers moved forward and popped flashbulbs in the faces of the Mercury Seven astronauts: from the Marine Corps, Lieutenant Colonel John H. Glenn, Jr.; from the Navy, Lieutenant Commander Walter M. Schirra, Jr., Lieutenant Commander Alan B. Shepard, Jr., and Lieutenant M. Scott Carpenter; and from the Air Force, Captain L. Gordon Cooper, Captain Virgil I. "Gus" Grissom, and Captain Donald K.

Slayton. A noise in the conference room rose to a roar as this photo shoot proceeded. Some of the journalists bolted for the door with the press kit to file their stories for the evening papers; others ogled the astronauts.

John Glenn picked up on the mood of the audience and delivered a ringing sermon on God, country, and family. "I think we would be most remiss in our duty," he said, "if we didn't make the fullest use of our talents in volunteering for something that is as important as this is to our country and to the world in general right now. This can mean an awful lot to this country, of course."[18] Near the end of the meeting, a reporter asked if they believed they would come back safely from space and all raised their hands. Glenn raised both of his.

The astronauts emerged as noble champions who would carry the nation's manifest destiny beyond its shores and into space. James Reston of the *New York Times* said he felt profoundly moved by the press conference. "What made them so exciting," he wrote, "was not that they said anything new but that they said all the old things with such fierce convictions.… They spoke of 'duty' and 'faith' and 'country' like Walt Whitman's pioneers.… This is a pretty cynical town, but nobody went away from these young men scoffing at their courage and idealism."[19]

The astronauts essentially became the personification of NASA to most Americans during the Mercury project, creating internal jealousies and turf battles over who controlled the spaceflight program. With their celebrity status, they exercised important influences over the direction of the program. Despite the periodic irritations between astronauts, engineers, and administrators, mostly disagreements were the exception rather than the rule and all parties spent most of their time working together to further the project's operational readiness.

The astronauts, about whom the public clamored for personal details, were cast by the press in the image of clean-cut "all American" boys whose mythical lives popularized family-oriented television programs during the 1950s and 1960s. The astronauts were portrayed as brave, God-fearing, patriotic individuals with loving wives and children. Addressing a joint session of Congress after his three orbits around the world in 1962, astronaut John Glenn announced to the wildly cheering crowd that "I still get a real hard-to-define feeling down inside when the flag goes by" and got away with it.[20] Glenn's sincerity in this statement is unquestioned, but some valued the astronauts more for their symbolism than for their capability.

The astronauts, despite heavy-handed NASA public affairs officials, were the "main architects" of their image. But they appeared at a time when NASA desperately needed to inspire public trust in its ability to carry out the nation's goals in space. They embodied the personal qualities in which Americans of that era wanted to believe: bravery, honesty, love of God and country, and family devotion. How could anyone distrust a government agency epitomized by such people? As one of the *Life* reporters summarized: "*Life* treated the men and their families with kid gloves. So did most of the rest of the press. These guys were heroes; most of them were very smooth, canny operators with all of the press. They felt that they had to live up to a public image of good clean all-American guys, and NASA knocked itself out to preserve that image."[21]

These astronauts put a very human face on the grandest technological endeavor in history, and the myth of the virtuous, no-nonsense, able, and professional astronaut was born with the unveiling of the Mercury Seven in 1959. In some respects, it was a natural occurrence. The Mercury Seven were each of us. At sum, those first astronauts established in public consciousness a representation of the best the United States had to offer the world. Throughout, Americans embraced the idea of the astronaut as making safe the way for the civilization to go forward into the cosmos.

Unbeknownst to NASA, soon after the Mercury Seven were announced, Randy Lovelace wanted to learn if women could perform in these tests as well as their male counterparts. Working with private funding provided by veteran pilot Jackie Cochran, Lovelace and Geraldyn "Jerrie" Cobb brought 18 other experienced female pilots to the Lovelace Clinic for secret testing, traveling alone or in pairs. Twelve of them did very well, and along with Jerrie Cobb, they eventually became known as the "Mercury 13." Some of them believed this would lead to their becoming NASA astronauts, despite the fact that NASA was not involved in the tests and had no knowledge of them.

News of these women's tests soon reached the media, and considerable excitement about America's first "lady astronauts" swept the country. Of course, when NASA learned of this effort, its leaders ended the testing and made clear that it had no plans during the space race to employ female astronauts.

This was not one of NASA's shining moments. At a House of Representatives hearing on this issue in July 1962, NASA Mercury program official George M. Low as well as Mercury astronauts John Glenn and Scott Carpenter testified that NASA's selection criteria would have excluded all women for the astronaut corps because astronauts were required to be graduates of military jet test piloting programs, and the military did not allow women in this field. Glenn went further: "The fact that women are not in this field is a fact of our social order."[22] This ended the initiative; it would be more than 25 years before the first women entered the astronaut corps, and more than 30 years until the first flew in space in 1983. In later years, Glenn regretted his testimony and confessed that he reflected in 1962 the circumstances of that time and place.

Conducting the Mercury Program

The astronauts worked hard to make Project Mercury a success, undergoing training far from their professional experience. In December 1959, John Glenn described for a colleague some of the stress and strain of the space program:

> Following our selection in April, we were assigned to the Space Task Group portion of NASA at Langley Field, and that is where we are based when not traveling. The way it has worked out, we have spent so much time on the road that Langley has amounted to a spot to come back to get clean skivvies and shirts and that's about all. We have had additional sessions at Wright Field in which we did heat chamber, pressure chamber, and centrifuge work and spent a couple of weeks this fall doing additional centrifuge work up at NADC, Johnsville, Pennsylvania. This was some program since we were running it in a lay-down position similar to that which we will use in the capsule later on and we got up to as high as 16 g's. That's a bitch in any attitude, lay-down or not.[23]

Project Mercury progressed too slowly for most observers between the origins of NASA and 5 May 1961, when Alan Shepard became the first American to reach space. Shepard's flight had been postponed for weeks so NASA engineers could resolve numerous details. It proved successful, but glitches and lengthy "holds" on the launch to fix problems marred the mission. In many ways, it was impressive—as the first American mission, it was celebrated throughout the nation—but its 15-minute ride to an altitude of only 116.5 statute miles paled in comparison to the orbital mission of Yuri Gagarin on 12 April 1961.

The second flight, a suborbital mission like Shepard's, launched on 21 July 1961, essentially duplicated the flight of Alan Shepard, and, like that earlier flight, also had problems. The hatch blew off prematurely from the Mercury capsule, Liberty Bell 7, and it sank to the bottom of the Atlantic Ocean. In the process, the astronaut, "Gus" Grissom, nearly drowned when his spacesuit filled with seawater before being hoisted to safety in a helicopter. These suborbital flights, however, proved valuable for the NASA technicians who found ways to solve or work around literally thousands of obstacles to successful spaceflight. Only in 1999 did a team led by Curt Newport find and recover Liberty Bell 7, undertake its restoration, and send it on a national tour. It is now at its place of display in the Kansas Cosmosphere in Hutchinson, Kansas.

Not until 20 February 1962 was NASA ready for an orbital flight with an astronaut. On that date, John Glenn became the first American to circle Earth, making three orbits in his Friendship 7 Mercury spacecraft. The flight was not without problems, however; Glenn flew parts of the last two orbits manually because of an autopilot failure and left his normally jettisoned retrorocket pack attached to his capsule during reentry because of a warning light showing a loose heat shield. Glenn's flight provided a healthy increase in national pride, making up for at least some of the earlier Soviet successes. The public, more than celebrating the technological success, embraced Glenn as a personification of heroism and dignity.

Three more successful Mercury flights took place during 1962 and 1963. Scott Carpenter made three orbits on 20 May 1962, and on 3 October 1962, Walter Schirra flew six orbits. The capstone of Project Mercury came on 15–16 May 1963 with the flight of Gordon Cooper, who circled Earth 22 times in 34 hours. The program had succeeded in accomplishing its purpose: to successfully orbit a human in space, to explore aspects of tracking and control, and to learn about microgravity and other biomedical issues associated with spaceflight. The range of human actions in space would expand significantly with NASA's follow-on programs.

Looking Forward

Even as these efforts proceeded, the realities of the Cold War shook NASA out of its "ivory tower" of deliberate scientific and technological development and transformed it into a powerful vehicle for competing with the Soviet Union. Heretofore, in line with Eisenhower's priorities, the Agency had avoided racing the Soviets. In a remarkable statement, T. Keith Glennan, the NASA Administrator, confided in his diary on 1 January 1960 that he would not conduct the activities of the U.S. space program in response to the Soviet Union. "We are not going to attempt to compete with the Russians on a shot-for-shot basis in attempts to achieve space spectaculars," he wrote, adding, "Our strategy must be to develop a program on our own terms which is designed to allow us to progress sensibly toward the goal of ultimate leadership in this competition."[24] While a rational position, this did not take into consideration the harshness of the Cold War environment of the early 1960s and the seemingly life-and-death struggle between the two superpowers. That competition ultimately dictated the activities of NASA for the balance of the decade, especially in relation to the United States' no-holds-barred sprint to the Moon known as Project Apollo.

CHAPTER 6

Reaching for the Moon

May is one of the nicest months of the year in the District of Columbia. The cherry blossoms are waning at the Tidal Basin, but it is still not overly warm, and the tourists have not yet overrun the monuments and museums in the Nation's capital. That would not be the case until after Memorial Day. In May 1961, Major League Baseball was under way, and even though the Washington Senators in the American League were never much of a contender, evenings at the ballpark were invariably pleasant. But for those working at the White House in the Kennedy administration, a sense of urgency ruled. The U.S.-Soviet Cold War had taken a new turn and President John F. Kennedy believed he had to take decisive action. He set in motion a succession of fact-finding reviews over what we might do in space that could directly respond to Soviet successes beyond Earth. The result was the Apollo program to land Americans on the Moon by the end of the decade. The goal was finally accomplished on 20 July 1969, when Apollo 11's astronaut Neil Armstrong stepped out of an ungainly lunar landing craft and set foot on the Moon.

Kennedy put into NASA leadership a well-known Washington insider to oversee this effort. A Democratic operative since the New Deal, James E. Webb served as NASA Administrator between January 1961 and November 1968. During his tenure, the space agency developed the modern techniques necessary to coordinate and direct the most unique and complex technological enterprise in human history: the sending of human beings to the Moon and bringing them safely back to Earth. A master at bureaucratic politics, Administrator Webb built a seamless web of political liaisons that brought continued support for and resources to accomplish the Apollo Moon landing on the schedule President Kennedy had announced.

Reevaluating NASA's Priorities

With an impact similar to that of the launch of Sputnik in 1957, the Soviet orbiting of the first human in space, cosmonaut Yuri Gagarin, on 12 April 1961, changed the situation in the U.S.-USSR rivalry in space. Two days after the Gagarin flight, Kennedy discussed the possibility of a lunar landing program with Jim Webb, but Kennedy delayed deciding when NASA's conservative estimates projected a cost of more than $30 billion, more than $250 billion in 2020 dollars.

That changed a week later when the embarrassing U.S.-backed Bay of Pigs invasion failed in Cuba. At that point, Kennedy called Vice President Lyndon B. Johnson to assess what policy changes might help change the subject from Kennedy administration failures. As he wrote in a memorandum to Johnson on 20 April 1961, do "we have a chance of beating the Soviets by…a trip around the moon, or by a rocket to land on the moon, or by a rocket to go to the moon and back with a man. Is there any other space program which promises dramatic results in which we could win?"[1] Johnson polled NASA leaders, as well as scientific and technical gurus, about a new space initiative. Among others, Wernher von Braun, Director of NASA's George C. Marshall Space Flight Center at Huntsville, Alabama, and head of a big rocket program needed for any lunar effort, told Johnson that "we have a sporting chance of sending a 3-man crew *around the moon* ahead of the Soviets" and "an excellent chance of beating the Soviets to the *first landing of a crew on the moon* (including return capability, of course)."[2]

After gaining these technical opinions, Johnson lined up political support for a Moon landing. He put it this way, "Would you rather have us be a second-rate nation or should we spend a little money?"[3] In an interim report to the President on 28 April 1961, Johnson recommended committing the nation to a lunar landing.

Decision (and Reconsideration)

President Kennedy unveiled the commitment to undertake Project Apollo on 25 May 1961, in a speech on "Urgent National Needs," billed as a second State of the Union message. He told Congress that the country faced extraordinary challenges and needed to respond extraordinarily. In announcing the lunar landing commitment, he said: "I believe this Nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish."[4]

Kennedy worried that Congress might balk at the Moon program's price tag. He said not once, but twice, that the costs would be great and that it would take many years to achieve success. He believed this was a prudent course of action but required the assent of the legislative branch. In his prepared remarks he warned: "Let me be clear that I am asking the Congress and the country to accept a firm commitment to a new course of action—a course which will last for many years and carry very heavy costs…. If we were to go only halfway, or reduce our sights in the face of difficulty, it would be better not to go at all."[5] Kennedy's hesitancy in pointing out the difficulties of the Moon landing commitment did not square with subsequent presidents and their bold announcements for going "back to the Moon, and on to Mars," especially the two Bush presidencies, which seemed to treat congressional approval as a foregone conclusion.[6] The hubris displayed on those occasions might have contributed to the failure to achieve them.

Kennedy mused upon returning to the White House after his "Urgent National Needs" speech that Congress might turn him down. His aides assured him that Johnson, a former master of the Senate, had lined up the necessary support, and that was indeed the case. Few expressed concerns either about the difficulty or about the expense at the time. Congressional debate proved perfunctory, although Kennedy's budget director, David Bell, worried that NASA would break the bank and recommended action at every turn to curtail the red ink.

It fell to NASA to accomplish the task set out in a few short paragraphs by JFK. By the time that the goal would be accomplished in 1969, few of the key figures associated with the decision would still be in leadership positions in the government. Kennedy fell victim to an assassin's bullet in November 1963, and Lyndon Johnson, of course, succeeded Kennedy as President but left office in January 1969, just a few months before the first landing. Even James Webb retired from office under something of a cloud in October 1968 following the Apollo fire that killed three astronauts. Hugh Dryden and several early supporters of Apollo in Congress died during the 1960s and never saw the program completed.

Even as the program got under way, the political consensus that had set it in motion began to crumble. The rapidly expanding NASA budget, always a target for opponents of the program, came under attack every year beginning in 1962. While the White House always protected the Apollo program, cuts from what NASA claimed it needed to do the program took their toll on the effort. Former President Dwight D. Eisenhower led the charge against the Moon landings in a 1962 article: "Why the great hurry to get to the moon and the planets? We have already demonstrated that in everything except the power of our booster rockets we are leading the world in scientific space exploration.

From here on, I think we should proceed in an orderly, scientific way, building one accomplishment on another."[7] Likewise, in the 1964 presidential election, Republican candidate Senator Barry Goldwater urged a reduction of the Apollo commitment to pay for national security initiatives.

Anticipating these attacks, Kennedy always hedged his bets in supporting Apollo. He harbored the possibility of making the program a joint effort with the Soviet Union. In his inaugural address in January 1961, Kennedy spoke directly to Soviet Premier Nikita Khrushchev and asked him to cooperate in exploring "the stars." In his State of the Union address 10 days later, he asked the Soviet Union "to join us in developing a weather prediction program, in a new communications satellite program, and in preparation for probing the distant planets of Mars and Venus, probes which may someday unlock the deepest secrets of the Universe."[8]

Within two weeks of giving his 25 May speech, Kennedy met Khrushchev at the Vienna summit and proposed making Apollo a joint mission with the Soviets. The Soviet leader reportedly first said no, then replied "why not?" and then changed his mind again, saying that disarmament was a prerequisite for U.S.-U.S.S.R. cooperation in space. Kennedy confided to James Webb that he felt vulnerable to the Republican charges concerning the Moon program and thought refashioning it into a cooperative effort could defuse the situation.

On 20 September 1963, Kennedy made a well-known speech before the United Nations, in which he again proposed a joint human mission to the Moon. He closed by urging, "Let us do the big things together."[9] In public, the Soviet Union was noncommittal. The Soviet official newspaper, *Pravda*, for example, dismissed the 1963 proposal as premature. Some have suggested that Khrushchev viewed the American offer as a ploy to open up Soviet society and compromise Soviet technology. Although these efforts did not produce any space agreements, the fact that Kennedy pursued various forms of space cooperation until his assassination in 1963 portended what might have resulted had he remained in office for a full two terms.

Harnessing Resources

When NASA learned of the President's decision to move forward with the Moon landing, its leaders reacted with the mixed emotions of excitement and anguish. They could finally realize many of their dreams for an aggressive space program. At the same time, it placed an enormous burden on the Agency. How would NASA go about accomplishing the President's goal? The technological challenge was enormous, and directing the Apollo effort required a special genius for organization and management.

The first issue NASA leaders faced was securing funding. While Congress enthusiastically appropriated the funding to start Apollo after Kennedy's decision, Jim Webb was rightly concerned that the momentary sense of crisis would subside and that the political consensus for Apollo would abate. So true. While the nation's political leadership had made an intellectual commitment, NASA's leadership was concerned that they might renege on the economic part of the bargain at some future date.

Initial NASA estimates of the costs of Project Apollo were between $20 and $30 billion through the end of the decade, over $200 billion in 2020 dollars when accounting for inflation. Webb quickly stretched those initial estimates for Apollo as far as possible, with the intent that even if NASA did not receive its full budget requests, as it did not during the latter half of the decade, it would still be able to complete Apollo. As it turned out, Webb was able to sustain the momentum of Apollo through the decade, largely because of his rapport with key members of Congress and with Lyndon Johnson, who became President in November 1963.

NASA leaders recognized that while the size of the task was enormous, it was still technologically and financially within their grasp, but they had to move forward quickly. Accordingly, the space agency's annual budget increased from $500 million in 1960 to a high point of $5.2 billion in 1965. The NASA funding level represented 5.3 percent of the federal budget in 1965, the highest in the Agency's history.

Out of the budgets appropriated for NASA each year, approximately 50 percent went directly for human spaceflight, and the vast majority of that went directly toward Apollo. During this era, Webb sought to expand the definition of Project Apollo beyond just the mission of landing humans on the Moon. As a result, even those projects not officially funded under the Apollo line item could be justified as supporting the mission.

Webb took this approach for essentially two reasons. First, he and the rest of the NASA leadership were committed to developing a broad-based space exploration program, not the execution of a single project, even one as far-reaching as Apollo. Unfortunately, because of the massive size of the lunar landing mission, and especially because of its cost, there was little opportunity to undertake additional large space exploration initiatives. Using Apollo as an umbrella to accomplish a host of scientific and technical activities offered a practical solution to the funding problem. Second, by attaching broad scientific and technical enterprises to Project Apollo, NASA incorporated various other groups and activities into the program and helped to elicit the continued support of those involved. While not entirely successful in this effort, the result was that much additional space science, education, and a host of other

Figure 6-1. This image is conspicuous because of the African American working in the wind tunnel test of the Saturn I at Langley Research Center, Hampton, Virginia, on 2 March 1963. There were few minorities at NASA at the time, and the space agency staged this image with an unnamed technician to demonstrate its commitment to equal opportunity. (NASA, L-1963-01637)

activities were carried out under the rubric of Apollo than might have been accomplished otherwise.

As a result of these strategies, NASA tried to hang every possible NASA program on the lunar mission so as to ensure its funding. For example, Webb argued that many scientific missions were required to support Apollo; the program, therefore, became an umbrella for such Moon probes as the Ranger, Lunar Orbiter, and Surveyor series, as Apollo required a system of radar tracking, telemetry, and communications. Using the hook of the lunar landing's need for great advances in science and technology, Webb sought to expand American education and research by channeling millions of dollars into the nation's educational institutions under the rubric of Apollo. The centerpiece of this effort was the Sustaining University Program inaugurated in 1962 in the name of Apollo. Accordingly, by 1970 NASA had paid the bills for the graduate educations of more than 5,000 scientists and engineers at a cost of over $100 million. It had also spent more than $32 million on the construction of university laboratories and given more than $50 million worth of multidisciplinary grants to some 50 universities.

Funding was not the only critical component for Project Apollo. To realize the goal of Apollo under the strict time constraints mandated by the President, personnel had to be mobilized. A recent study estimates that approximately 1 in 20 Americans worked on some aspect of the Apollo program during its existence. They might not have been so integrally involved that they recognized a direct linkage, and certainly not all supported it at any given time, but Apollo's presence was pervasive in American business and society. Carried to its most extreme, if an individual worked for a company that produced a part used in some technology associated with Apollo, then that individual could claim a role, however tenuous, in accomplishing the lunar landing mission. These roles took two forms. First, by 1966 the Agency's civil service rolls had grown to 36,000 people from the 10,000 employed at NASA in 1960. Additionally, NASA's leaders made an early decision that they would have to rely on outside researchers and technicians to complete Apollo, and contractor employees working directly on the program increased by a factor of 10, from 36,500 in 1960 to 376,700 in 1965. Private industry, research institutions, and universities, therefore, provided the majority of personnel working on Apollo.

To incorporate the great amount of work undertaken for the project into the formal NASA bureaucracy never seemed a particularly savvy idea, and as a result during the 1960s somewhere between 80 and 90 percent of NASA's overall budget went for contracts to purchase goods and services from others. It was lost neither on NASA officials nor on Congress that government contracts to the private sector ensured greater support for the program as a whole.

In addition to these other resources, NASA moved quickly during the early 1960s to expand its physical capacity so that it could accomplish Apollo. In 1960, the space agency consisted of a small headquarters in Washington, its three inherited NACA research centers, the Jet Propulsion Laboratory, the

Goddard Space Flight Center, and the Marshall Space Flight Center. With the advent of Apollo, these installations grew rapidly. In addition, NASA added four new facilities specifically to meet the demands of the lunar landing program. In 1962, it created the Manned Spacecraft Center (renamed the Lyndon B. Johnson Space Center in 1973), near Houston, Texas, to design the Apollo spacecraft and the launch platform for the lunar lander. This Center also became the home of NASA's astronauts and the site of Mission Control. NASA then greatly expanded for Apollo the Launch Operations Center at Cape Canaveral on Florida's eastern seacoast. Renamed the John F. Kennedy Space Center on 29 November 1963, this installation's massive and expensive Launch Complex 39 was the site of all Apollo/Saturn V firings. To support the development of the Saturn launch vehicle, in October 1961 NASA created on a Deep South bayou the Mississippi Test Facility, renamed the John C. Stennis Space Center in 1988. Finally, in 1962 it established the Electronic Research Center in Cambridge, Massachusetts, near MIT, the only NASA Center ever fully closed after the buildup for the Apollo program. The cost of this expansion was great, more than $2.2 billion over the decade, with 90 percent of it expended before 1966.

Implementing a "Program Management Concept"

The Project Mercury management approach had been quite successful, but the massive Apollo program that took Americans to the Moon in the 1960s and 1970s required a more structured approach. NASA borrowed for Apollo the program management concept used by the Department of Defense in building the first intercontinental ballistic missiles. To accomplish its goal, NASA had to meld disparate institutional cultures and approaches into an inclusive organization moving along a single unified path. Each NASA installation, university, contractor, and research facility had its own perspective on how to go about the task of accomplishing Apollo.

The central figure in implementing this more rigorous approach was U.S. Air Force Major General Samuel C. Phillips, the architect of the Minuteman ICBM program before coming to NASA in 1962. Answering directly to the Office of Manned Space Flight at NASA Headquarters, which in turn reported to the NASA Administrator, Phillips created an omnipotent program office with centralized authority over design, engineering, procurement, testing, construction, manufacturing, spare parts, logistics, training, and operations.

One of the fundamental tenets of the program management concept was that three critical factors—cost, schedule, and reliability—were interrelated and had to be managed as a group. Many also recognized these factors' constancy;

if program managers held cost to a specific level, then one of the other two factors, or both of them to a somewhat lesser degree, would be adversely affected. This held true for the Apollo program. The schedule, dictated by the President, was firm. Since humans were involved in the flights, and since the President had directed that the lunar landing be conducted safely, the program managers placed a heavy emphasis on reliability. Accordingly, Apollo used redundant systems extensively, but the emphasis on both of these factors forced the third factor, cost, much higher than might have been the case otherwise. To keep all of this in order, project managers put into place elaborate systems engineering concepts requiring enormous staffs to effectively coordinate the development and integration of these technologies.

The program management concept was recognized as a critical component of Project Apollo's success in November 1968, when *Science* magazine, the publication of the American Association for the Advancement of Science, observed:

> In terms of numbers of dollars or of men, NASA has not been our largest national undertaking, but in terms of complexity, rate of growth, and technological sophistication it has been unique…. It may turn out that [the space program's] most valuable spin-off of all will be human rather than technological: better knowledge of how to plan, coordinate, and monitor the multitudinous and varied activities of the organizations required to accomplish great social undertakings.[10]

Understanding the management of complex structures for the successful completion of a multifarious task was an important outgrowth of the Apollo effort.

Under Phillips, this management concept orchestrated more than 500 contractors working on both large and small aspects of Apollo. For example, the prime contracts awarded to industry for the principal components of just the Saturn V included the Boeing Company for the S-IC, first stage; North American Aviation, S-II, second stage; the Douglas Aircraft Corporation, S-IVB, third stage; the Rocketdyne Division of North American Aviation, J-2 and F-1 engines; and International Business Machines (IBM), Saturn instruments. These prime contractors, with more than 250 subcontractors, provided millions of components for use in the Saturn launch vehicle, all meeting exacting specifications for performance and reliability. So huge was the overall Apollo endeavor that NASA's procurement actions rose from roughly 44,000 in 1960 to almost 300,000 by 1965.

Getting all of the personnel elements to work together challenged the program managers, regardless of whether or not they were civil service, industry, or university personnel. These communities were not monolithic, and differences among them thrived. NASA leadership generally viewed this pluralism as a positive force within the space program, for it ensured that all sides aired their views and emphasized the honing of positions to a fine edge. Competition, most people concluded, made for a more precise and viable space exploration effort. There were winners and losers in this strife, however, and Apollo program leaders worked hard to keep these factors balanced and orderly so NASA could accomplish its goals.

Another important management issue arose from the Agency's inherited culture of in-house research. Because of the magnitude of Project Apollo and its time schedule, most of the nitty-gritty work had to be done outside NASA by contractors. As a result, with a few important exceptions, NASA scientists and engineers planned the program, prepared guidelines for execution, competed contracts, and oversaw work accomplished elsewhere. This grated on those NASA personnel oriented toward research and prompted disagreements over how to carry out the lunar landing goal. Of course, they had reason for complaint beyond the simplistic argument of wanting to be "dirty-handed" engineers; they had to have enough in-house expertise to ensure program accomplishment. If scientists or engineers did not have a professional competence on par with the individuals actually doing the work, how could they oversee contractors actually creating the hardware and performing the experiments necessary to meet the rigors of the mission?

One anecdote illustrates this point. The Saturn second stage was built by North American Aviation at its plant at Seal Beach, California; shipped to NASA's Marshall Space Flight Center, Huntsville, Alabama; and there tested to ensure that it met contract specifications. Problems developed on this piece of the Saturn effort, and Wernher von Braun began intensive investigations. Essentially his engineers completely disassembled and examined every part of every stage delivered by North American to ensure no defects. This was an enormously expensive and time-consuming process, grinding the stage's production schedule almost to a standstill and jeopardizing the presidential timetable.

When this happened, Webb told von Braun to desist, adding that "We've got to trust American industry."[11] The issue came to a showdown at a meeting where the Marshall rocket team was asked to explain its extreme measures. While doing so, one of the engineers produced a rag and told Webb that "this is what we find in this stuff."[12] The contractors, the Marshall engineers believed, required extensive oversight to ensure they produced the highest quality work. A compromise emerged ensuring a 10 percent contingency on project contracts to check contractor reliability.

The program management concept worked well, but it proved expensive. NASA officials realized that at the conclusion of the Apollo program they would never again have the resources that had been made available for the Moon landings and they had to find other means of accomplishing their projects without such broad expenditures. Perhaps most important, the experience of Apollo suggested that this approach was fragile and could easily become flawed if its managers failed to manage practices strictly. In the face of conflicting organizational demands, the practices so successful in Apollo would tend to disappear. Maintaining such practices required vigilance and adjustment always.

Developing Expertise: Project Gemini

To expand the skills necessary to land on the Moon, NASA inaugurated a second human spaceflight program to bridge the gap between Mercury and Apollo. Project Gemini achieved this end. Hatched in the fall of 1961 by engineers at Robert Gilruth's Space Task Group in cooperation with McDonnell Aircraft Corp., the program flew in the 1965–66 era and truly demonstrated the skills that would be necessary to conduct the Moon landings. The Gemini capsule could accommodate two astronauts for extended flights of more than two weeks. The project pioneered the use of fuel cells instead of batteries to power the ship and incorporated a series of important advances in technology. The whole system reached space on a modified Titan II launch vehicle, another ballistic missile developed for the Air Force. The Gemini engineers perfected techniques for rendezvous, docking, and spacewalking (or extravehicular activity). Intended initially as an inexpensive effort, Gemini costs soon shot up from $350 million to over $1 billion. Everyone gulped but supported the increases in the name of achieving the Moon landings by the end of the decade.

Another part of the Gemini program was an attempt to pioneer the capability to land on a runway after return from space, rather than to parachute into the ocean and be rescued at sea. NASA engineers studied how to undertake a controlled descent and landing by deploying an inflatable paraglider wing. First NASA built and tested the Paresev, a single-seat, rigid strut parasail, designed much like a huge hang glider, to test the possibility of a runway landing. The space agency then contracted with North American Aviation, Inc. to undertake a design, development, and test program for a scaled-up spacecraft version of the concept. A full-scale, two-pilot Test Tow Vehicle (TTV) was also built to test the concept and train Gemini astronauts for flight. The system never worked well enough to use on the Gemini program. Even though this R&D effort proved less successful than originally envisioned, NASA engineers kept pushing back deployment of the paraglider, suggesting that the first few missions could use conventional parachutes but later flights would incorporate the paraglider. At one point in 1964, NASA wanted to have the first seven Gemini capsules use a traditional parachute recovery system, with the last three missions employing the paraglider. This proved a pipe dream as well, and NASA eventually abandoned it.

Why did this effort fail? Deploying an inflatable structure from the capsule and gliding it to a landing on the surface is a task not without difficulties. The project leaders were never able to overcome the technical challenges. If it was not the deployment, it was the control mechanism. If neither of those, it was the difficulty of piloting it. If none of those, it was the size and weight of the paraglider in relation to the capacity of the Gemini capsule.

The first astronaut flight of Gemini took place on 23 March 1965, when Mercury veteran Gus Grissom and John W. Young, a naval aviator chosen as an astronaut in 1962, flew Gemini III. The next mission, flown in June 1965, stayed aloft for four days, and astronaut Edward H. White II performed the first American extravehicular activity (EVA), or spacewalk. Eight more missions followed through November 1966.

Virtually all of those missions had unique problems. The flight of Gemini VIII, in the spring of 1966, proved difficult as astronauts Neil Armstrong and David Scott sought to rendezvous and dock with an Agena target vehicle. The crew docked with it as planned, but the joined spacecraft began a roll. Armstrong used Gemini's orbital maneuvering system to stop the roll, but the moment he stopped using the thrusters, it started again. They undocked with the Agena, but Gemini VIII continued to roll at about one revolution per second. After a lengthy process of steadying the spacecraft, Armstrong and Scott tested each thruster on the capsule and found that number 8 was stuck in the on position, causing the roll. The mission then returned to Earth one orbit later. Investigators determined that an electrical short had caused a static electricity discharge and astronauts Armstrong and Scott had salvaged the mission through their actions.

Likewise, while Ed White enjoyed his spacewalk, he had no duties outside the spacecraft. Not so with the spacewalk of Gene Cernan during Gemini IX on 5 June 1966. It was only the second time an American astronaut had ever ventured outside of a capsule to expose the body to the extreme environment of space, and it nearly proved fatal. Cernan quickly learned that anything he did in microgravity took more energy than anticipated and his body overheated. This overtaxed his spacesuit's environmental system; his helmet visor fogged over, sweat poured into his eyes, and his heart raced to more than three times its normal rate. Finally, after more than 2 hours and one and a half orbits of Earth, a decimated Gene Cernan made it back inside the capsule after failing to complete most of the objectives of his EVA. At the same time, NASA learned a valuable lesson about the fragility of the human body in the extreme environment

Figure 6-2. This time-exposure photograph shows the configuration at the launch of Gemini X on 18 July 1966. On board the spacecraft were John W. Young and Michael Collins. (NASA, s66-42762)

of space. Its engineers redesigned spacesuits to provide more robust life support, and led by Buzz Aldrin, the astronauts developed procedures to conduct useful work more effectively in the harsh extremes of space.

These difficulties forced NASA to make innumerable changes to the Gemini spacecraft and to develop procedures for rendezvous, docking, and spacewalking.

On Gemini XII, between 11 and 15 November 1966, Buzz Aldrin made his first flight, demonstrating the capabilities mastered through the Gemini program. During that mission Aldrin manually recomputed all the rendezvous maneuvers after the onboard radar failed. Aldrin also engaged in a 2-hour spacewalk that became the longest and most successful ever done to that time. In a 4-day, 59-revolution flight that successfully ended the Gemini program, he perfected and demonstrated theories of rendezvous and docking of spacecraft in orbit that he had studied while obtaining an astronautics Ph.D. at MIT. In essence, this mission conquered the difficulties previously experienced by NASA in space rendezvous and docking. After this demonstration of capability, Gemini XII became the last Gemini to enter space, opening the way for the new Apollo missions.

By the end of the Gemini program in the fall of 1966, orbital rendezvous and docking had become standard, and it seemed clear that humans could live, work, and stay healthy in space for more than two weeks at a time. Above all, the program had added nearly 1,000 hours of valuable spaceflight experience in the years between Mercury and Apollo, which by 1966 was nearing flight readiness. In every instance, NASA had enhanced the role of the astronauts as critical fliers of spacecraft, a role that would become even more significant in the accomplishment of the Moon landings between 1969 and 1972.

Learning About the Moon

In addition to the necessity of acquiring the skills required to maneuver in space prior to executing the Apollo mandate, NASA had to learn much more about the Moon itself to ensure that its astronauts would survive. Of course, by the early part of the 20th century many of the physical features of the Moon's near side had been determined by ground-based astronomers who had been quietly working for centuries to create the map that the scientists of the Apollo program used as a starting point for their explorations. Yet many questions remained unanswered. These included: What was the Moon's origin? How did the Moon form, at the time of the solar system or by capture at a later time? Did the Moon have a rocky or dusty surface? Would the Moon's crust support any weight or swallow up anything that landed on it? How did the craters form, via meteor strike or volcanic or some other activity? Did life ever exist in any form on the Moon? Would communications systems work on the Moon? Would other factors—geology, geography, radiation, and so on—affect the astronauts?

To answer these questions, three distinct satellite research programs emerged to study the Moon. The first of these was Project Ranger, which had actually been started in the 1950s, in response to Soviet lunar exploration, but had been a notable failure until the mid-1960s when three probes photographed the lunar surface before crashing into it in the middle part of the decade.

The second project was the Lunar Orbiter, an effort approved in 1960 to place probes in orbit around the Moon. This project, originally not intended to support Apollo, was reconfigured in 1962 and 1963 to further the Kennedy mandate more specifically by mapping the surface. In addition to a powerful camera that could send photographs to Earth tracking stations, it carried three scientific experiments—selnodesy (the lunar equivalent of geodesy), meteoroid detection, and radiation measurement. While the returns from these instruments interested scientists in and of themselves, they were critical to Apollo. NASA launched five Lunar Orbiter satellites between 10 August 1966 and 1 August 1967, all successfully achieving their objectives. At the completion of the third mission, moreover, the Apollo planners announced that they had sufficient data to press on with an astronaut landing and were able to use the last two missions for other activities.

NASA also undertook a soft-landing program on the Moon, and Surveyor 1 reached the surface in June 1966. Carrying two cameras, Surveyor 1 provided multiple images of the surrounding lunar terrain and nearby surface materials. The onboard camera on Surveyor 1 returned more than 11,000 images over six weeks. Most images showed the lunar surface to a distance of more than a mile and offered close-ups never available before.

After a failure of Surveyor 2 on 22 September 1966, NASA's Surveyor 3 successfully soft landed on the lunar surface on 17 April 1967, providing imagery and soil analysis. The lander "bounced" more than once on the surface before coming to rest. Footprints from the initial impact were visible from the final landing site. Besides a camera similar to Surveyor 1, this lander also carried a mechanical scoop that dug several small trenches in the lunar soil. Over the next three weeks, the camera returned more than 6,300 images showing the surrounding rocks and the movements of the scoop. Two years after landing, Surveyor 3 was visited by the Apollo 12 astronauts. The television camera and other sections were removed and returned to Earth. The camera was later put on display in the Smithsonian Institution's National Air and Space Museum.

Although NASA lost contact with Surveyor 4 on 17 July 1967, it was followed with Surveyors 5, 6, and 7 over the course of the next few months. Most interesting, on 17 November Surveyor 6 became the first spacecraft to take off from the lunar surface. Controllers noted enough fuel remained for a brief firing of the retrorockets. Surveyor 6 performed a "hop," reaching a height of about 10 feet and coming to rest about 8 feet from its first position. Both sets of footprints in the lunar soil were plainly visible in images from the television camera. As a last mission, Surveyor 7 landed on 10 January

1968 north of the crater Tycho. In all, five of the seven Surveyor spacecraft completed their missions.

While all of this activity took place, teams of scientists assessed the potential for landing sites for the Apollo program. Everyone had their favorite locations, and teams contended for decisions in favor of their first choices. Some wanted to go to mountain ranges that promised unique types of geology. Others, especially engineers more concerned about the difficulties of landing in mountainous terrain, argued for the open expanses of the flatter terrain. These debates continued throughout the Apollo program, with more daring and geologically interesting sites added to later missions as experience overcame earlier fears.

Likewise, the astronauts who were to conduct these lunar landing missions had to be taught the basics of lunar geology and how to undertake fieldwork on the Moon. Most of them had little background in geology, but scientists offered them what amounted to an intensive M.S.-level education in lunar geology. Some learned enthusiastically and others reluctantly, but all completed an aggressive training effort to understand the geology of Moon. Many are aware that Apollo 17's Harrison Schmitt was a Harvard-trained Ph.D. in geology, but all of the astronauts worked hard to ensure that they undertook useful fieldwork on the lunar surface, and to a surprising degree they succeeded.

Public Perceptions of Apollo

The belief that Apollo enjoyed enthusiastic support during the 1960s and that somehow NASA has lost its compass thereafter enjoys broad appeal. Repeatedly, a chorus of remorse for lukewarm popular support enjoyed by specific space exploration activities in the present is followed with a heavy sigh and the conclusion, if only NASA's current efforts had the same level of commitment enjoyed by Apollo, all would be well.

While there may be reason to accept that Apollo was enormously important at some basic level, assuming a generally rosy public acceptance of it is incorrect. Indeed, the public's support for space funding has remained remarkably stable at approximately 80 percent in favor of the status quo since 1965, with only one significant dip in support in the early 1970s. For example, in the summer of 1965, one-third of the nation favored cutting the space budget, while only 16 percent wanted to increase it. During the next three and one half years, the number in favor of cutting space spending went up to 40 percent, with those preferring an increase dropping to 14 percent.

At the end of 1965, the *New York Times* reported that a poll conducted in six American cities showed five other public issues holding priority over efforts in outer space. Polls in the 1960s also consistently ranked spaceflight near the top of those programs to be cut in the federal budget. Most Americans seemingly preferred doing something about air and water pollution, job training for unskilled workers, national beautification, and poverty before spending federal funds on human spaceflight. The following year, *Newsweek* echoed the *Times* story, stating: "The U.S. space program is in decline. The Vietnam war and the desperate conditions of the nation's poor and its cities—which make space flight seem, in comparison, like an embarrassing national self-indulgence—have combined to drag down a program where the sky was no longer the limit."[13]

Nor did lunar exploration in and of itself create much of a groundswell of support from the general public. The American public during the 1960s largely showed hesitancy to "race" the Soviet Union to the Moon, and at only one point, October 1965, did even 50 percent of the public support human lunar exploration. In the post-Apollo era, the American public has continued to question the validity of undertaking human expeditions to the Moon. Public opinion suggests, instead, that the political crisis that brought public support to the initial lunar landing decision in 1961 was fleeting, and within a short period the coalition that announced it began to reconsider their decision. It also suggests that the public, more than anything else, questioned the costs associated with going to the Moon. What enthusiasm it may have enjoyed waned over

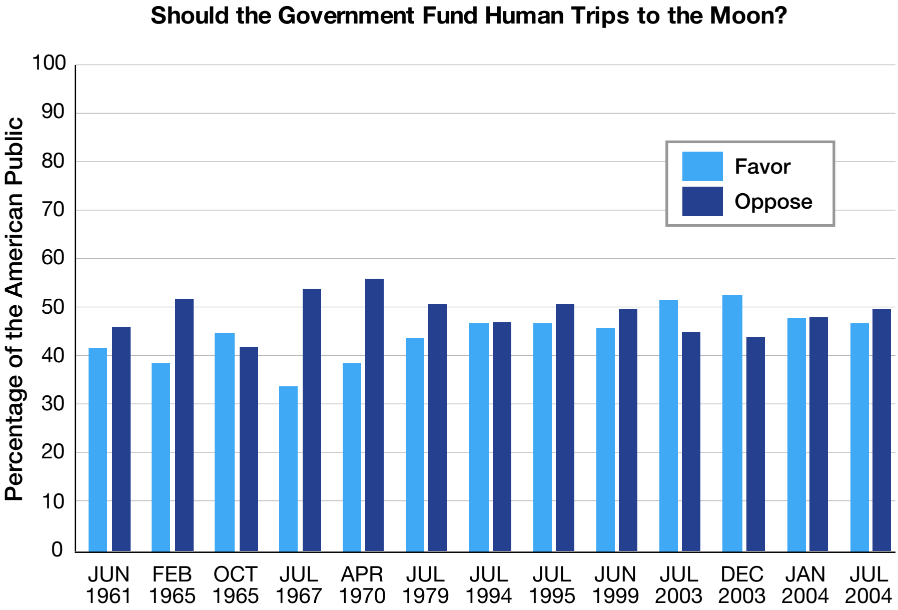

Figure 6-3. Should the government fund human trips to the Moon? (Sources: Gallup, Harris, NBC/Associated Press, CBS/New York Times Polls, CNN/USAT, Zogby, AP by Ipsos-Public Affairs, wording for questions differed slightly)

time, until by the end of the Apollo program in December 1972, the collapsing public support was apparent even to the most diehard NASA supporters. None of this, however, calls into question the very real excitement that the Apollo 11 Moon landing generated in the summer of 1969. Virtually every American was proud of the accomplishment; mostly they did not want to pay for it.

Thereafter, for science-minded students who witnessed Apollo in their formative years, the Moon landings served as an inspiration to pursue science, technology, engineering, and mathematics (STEM) in their education and professions. In a survey of 800 scientists and engineers in 2009, journalist Richard Monastersky reported in *Nature* that more than half claimed to have been inspired to train in science by the Moon landings. "I became completely space crazy," said one life scientist. "I was certain I'd be an astronaut. My interest shifted to biology, but I still believe Apollo 11 was a major influence on me."[14] In retrospect, therefore, the public as a whole was less than supportive of the program, mostly because of the costs involved, but many students were excited by it and pursued scientific and technical careers in part because of its inspiration.

NASA's Most Risky Apollo Decisions

During the Apollo program, NASA officials made thousands of critical, difficult, and risky decisions. Some of them did not work as intended, but largely they succeeded. Contracting out to industry for much of the work; harnessing personnel, funding, and other resources; using the program management concept; and a host of other issues were examples of a challenging decision-making environment. Three examples of outstanding decision-making include 1) the lunar landing mode decision, 2) the all-up testing decision, and 3) the circumlunar flight decision.

The Lunar Landing Mode Decision

An early management decision that had to be made by NASA before the equipment necessary for the Moon landing could be built involved the method of going, landing, and returning from the Moon. A wide range of possibilities existed, some of them outrageous, others impractical, and still others possible but perhaps not optimum. One of the most outrageous involved sending an astronaut in a small lander to the lunar surface, asking him to hike to a prelanded resupply module, and to live there until NASA could send another ship to rescue him. One that NASA engineers quickly recognized as impractical—Direct Ascent—called for the construction of a huge booster that launched a spacecraft, sent it on a course directly to the Moon, landed a large vehicle, and then returned to Earth. This proved technologically out of reach in terms of the schedule NASA was on to reach the Moon by the end of the decade. The method had few advocates when serious planning for Apollo began.

Only two approaches really mattered in the landing mode decision. Earth-orbit rendezvous had a powerful advocate in Wernher von Braun, Director of NASA's Marshall Space Flight Center, in no small matter because he recognized that it could lead to the building of space infrastructure in Earth orbit which had broad application beyond a sprint to the Moon. Launching various modules required for the Moon trip into Earth orbit, assembling a Moon ship, and sending it to the lunar surface had real appeal. It could be accomplished using the Saturn V launch vehicle already under development by NASA and capable of generating 7.5 million pounds of thrust. This method of reaching the Moon, however, was also fraught with challenges, notably finding methods of maneuvering and rendezvousing in space, assembling components in a weightless environment, and safely refueling spacecraft.

A counter to Earth-orbit rendezvous was what came to be called lunar-orbit rendezvous. It launched the entire lunar assembly on a single Saturn V, reaching the Moon, orbiting, and dispatching a small lander to the lunar surface. It was the simplest of the three methods, both in terms of development and operational costs, but it was risky. Since rendezvous was taking place in lunar orbit instead of Earth orbit, there was no room for error or the crew could not get home. Moreover, some of the trickiest course corrections and maneuvers had to be done after the spacecraft had been committed to a circumlunar flight. The Earth-orbit rendezvous approach kept all the options for the mission open longer than the lunar-orbit rendezvous mode.

John C. Houbolt, head of NASA's Rendezvous Panel at the Langley Research Center, Virginia, championed lunar-orbit rendezvous to the extent that he became persona non grata in some circles both at NASA Headquarters and at the Marshall Space Flight Center. Eventually, he went over the heads of several superiors and appealed directly to NASA Associate Administrator Robert C. Seamans, who responded to his entreaties by asking that the concept be given a full vetting. Using sophisticated technical and economic arguments, over a period of months in 1961 and 1962, Houbolt's group advocated and persuaded the rest of NASA's leadership that lunar-orbit rendezvous was not the risky proposition that it had earlier seemed.

The last to give in was Wernher von Braun. He favored the Earth-orbit rendezvous because the direct ascent approach was technologically unfeasible before the end of the 1960s, because it provided a logical rationale for a space station, and because it ensured an extension of the Marshall workload (something that was always important to Center Directors competing inside the Agency for personnel and other resources). At an all-day meeting on 7 June 1962 at Marshall, NASA leaders met to hash out these differences, with the debate getting heated at times. After more than 6 hours of discussion von Braun finally gave in to the lunar-orbit rendezvous mode, saying that its advocates had demonstrated adequately its feasibility and that any further contention would jeopardize the President's timetable. The lunar-orbit rendezvous mode became the approach the space agency took and was announced as a final decision on 7 November 1962. This gutsy call proved out, working well throughout the Apollo program.

The All-Up Testing Decision

The thunderous roar of the first static test of the Saturn V second stage on 16 April 1965 brought home to many the sheer power of the rocket that would take Americans to the Moon by the end of decade. Consisting of five engines burning liquid oxygen and liquid hydrogen, this stage could deliver 1 million pounds of thrust. It was critical to sending the Apollo spacecraft into Earth orbit, but it was also always behind schedule and required constant attention and additional funding. Parenthetically, the Soviet Union also pressed forward on their own comparable Moon rocket, the N-1, but never was able to get it to work properly. More than any other technical issue, the N-1's problems proved the difference between American success with Apollo and Soviet failure with their Moon landing program.

The Saturn V's second stage symbolized the challenges of building the Moon rocket. The hyper-cautious von Braun "Rocket Team" took minutely incremental approaches toward test and verification. They tested each component of each system individually and then assembled them for a long series of ground tests. Then they would test each stage individually before assembling the whole system for a long series of flight tests.

While this practice ensured thoroughness, it was both costly and time-consuming, and NASA had neither to expend during the Moon race. George E. Mueller, the head of NASA's Office of Manned Space Flight, disagreed with this approach. Drawing on his experience with the Air Force and aerospace industry, and shadowed by the twin bugaboos of schedule and cost, Mueller advocated what he called the "all-up" concept, in which the entire Apollo-Saturn system was tested together in flight without laborious preliminaries.

A calculated gamble, the first Saturn V test launch took place on 9 November 1967, with the entire Apollo-Saturn combination. A second test followed on 4 April 1968 for Apollo 6, but this time two J-2 engines in the second stage shut down prematurely because the hydrogen line that fed the engine igniters broke due to vibration. This led to a less-than-optimal parking orbit over Earth. Furthermore, the Saturn V's third stage, which had to fire from the parking orbit to place the Apollo spacecraft on a lunar trajectory, failed to restart. Although Apollo 6 did not complete all of its objectives, George Mueller declared that the test program had been successfully completed and that the next launch would have astronauts aboard. The gamble paid off. In 17 test and 15 piloted launches, the Saturn booster family scored a 100 percent launch reliability rate. It was this rocket technology that took the astronauts to the Moon in the latter 1960s and early 1970s.

The Circumlunar Flight Decision

NASA had faced a remarkably difficult year in 1967. On 27 January 1967, a capsule fire at Kennedy Space Center had killed three astronauts—Gus Grissom, Ed White, and Roger Chaffee—sending the Agency into months of recriminations, soul-searching, technical investigation, and hardware modification to recover. Apollo 7—with Wally Schirra, Walt Cunningham, and Donn Eisele—had helped greatly in setting Apollo back on track for a landing before the end of the decade, but NASA officials believed a major leap forward needed to take place to ensure a timely lunar landing. The circumlunar flight of Apollo 8 was the result. Although the mission was planned to test Apollo hardware in low Earth orbit, senior engineer George M. Low of the Manned Spacecraft Center at Houston, Texas, and USAF General Samuel C. Phillips, Apollo Program Manager at NASA Headquarters, pressed for approval to make it a circumlunar flight. The advantages of this could be important, both in technical and scientific knowledge gained as well as in a public demonstration of what the United States could achieve.

In the summer of 1968, Low broached the idea to Phillips, who then carried it to NASA Administrator James Webb, and in November the Agency reconfigured the mission for a lunar trip. They were in part responding to the Zond 5 circumlunar mission the Soviet Union launched on 15 September 1968, and although it flew without cosmonauts aboard, it was theoretically capable of carrying them. NASA officials wondered if the Soviets were planning to beat the United States to a circumlunar flight.

On 11 November, the Soviet Union launched Zond 6, and it also successfully circumnavigated the Moon before returning to Earth. By coincidence, on the day of the Zond 6 launch, Apollo program manager Phillips sent a memorandum to the NASA Administrator recommending that NASA get off the dime and fly the very next Apollo mission to the Moon. He recognized that it was a bold strategy, but it would regain American momentum in the race.

Phillips outlined a series of pros and cons for this decision, never mentioning the Soviet Zond effort but clearly alluding to demonstrated Soviet capabilities. NASA Administrator Webb accepted Phillips's recommendations on 18 November 1968 and made possible the dramatic mission of Apollo 8 on 21–27 December 1968, one of the most significant single flights of the entire program. Only the actual landing of Apollo 11 in July 1969 holds more symbolic importance in the space race than the circumlunar flight of December 1968. Apollo 8 had been a sporty mission. Christopher C. Kraft, director of NASA's Mission Control, called the decision "gutsy" since he estimated it had a 50-50 chance of success. Succeed it did, and in spectacular fashion.

Building Apollo Hardware

Three distinct types of Apollo hardware had to be developed to achieve the Apollo Moon landing. The first was the Saturn V Moon rocket. NASA had acquired the Wernher von Braun "Rocket Team" from the Army in the 1960s and put them to work on the Saturn family of launch vehicles. The Saturn I was solely a research and development vehicle that would lead toward the accomplishment of Apollo, making 10 flights between October 1961 and July 1965. The next step in Saturn development came with the maturation of the Saturn IB, an upgraded version of the earlier vehicle. With more powerful engines, generating 1.6 million pounds of thrust from the first stage, the first flight on 26 February 1966 tested the capability of the booster and the Apollo capsule in a suborbital flight.

The largest launch vehicle of this family, the Saturn V, represented the culmination of those earlier booster development and test programs. Standing 363 feet tall, with three stages, this was the vehicle that took astronauts to the Moon and returned them safely to Earth. The first stage generated 7.5 million pounds of thrust from five massive engines developed for the system. These engines, known as the F-1, were some of the most significant engineering accomplishments of the program, requiring the development of new alloys and different construction techniques to withstand the extreme heat and shock of firing. By 1968, having been demonstrated in the circumlunar flight of Apollo 8 in December, the Saturn V was ready to support the astronauts' lunar landings.

Meantime, work on the Apollo spacecraft—a capsule for the crew and a service module for life support, consumables, and equipment—stretched from 28 November 1961, when the prime contract for its development was awarded to North American Aviation, to 22 October 1968, when the last test flight took place. In between, there were various efforts to design, build, and test the spacecraft both on the ground and in suborbital and orbital flights. For instance, on 13 May 1964, NASA tested a boilerplate model of the Apollo capsule atop a stubby Little Joe II military booster, and another Apollo capsule actually achieved orbit on 18 September 1964, when it was launched atop a Saturn I. By the end of 1966, NASA leaders had declared the Apollo Command Module ready for human occupancy. The final flight checkout of the spacecraft prior to the lunar flight took place on 11–22 October 1968, with three astronauts during Apollo 7.

Two failures on the Apollo spacecraft nearly ended the program. The first was the capsule fire of 27 January 1967, in the Apollo-Saturn (AS) 204 during a ground test. The loss of three astronauts—Gus Grissom, Edward White, and Roger B. Chaffee—caused shock throughout the nation. James Webb, NASA Administrator, told the media at the time, "We've always known that something like this was going to happen sooner or later…who would have thought that the first tragedy would be on the ground?"[15]

The day after the fire, NASA appointed an eight-member investigation board, chaired by longtime NASA official and Director of the Langley Research Center, Floyd L. Thompson. It set out to discover the details of the tragedy: what happened, why it happened, whether it could happen again, what was at fault, and how could NASA recover? The members of the board learned that the fire had been caused by a short circuit in the electrical system that ignited combustible materials in the spacecraft fed by the oxygen-rich atmosphere. They also found that it could have been prevented and called for several modifications to the spacecraft, including a move to a less oxygen-rich environment. Changes to the capsule followed quickly—including a hatch that opened outward—and within a little more than a year it was ready for flight.

Webb reported these findings to various congressional committees and took a personal grilling at every meeting. The media also attacked him. While the ordeal was personally taxing, whether by happenstance or design, Webb deflected much of the backlash over the fire from both NASA as an agency and from the Johnson administration. While he was personally tarred with the disaster, the space agency's image and popular support was largely undamaged. Webb himself never recovered from the stigma of the fire, and when he left NASA in October 1968, even as Apollo was nearing a successful completion, he questioned the exemplary model for complex accomplishments at NASA that he had previously championed.

The second failure of the Apollo spacecraft came during the flight of Apollo 13 in 1970. After 56 hours, while Apollo 13 was en route to the Moon, an oxygen tank in the Service Module ruptured and damaged several of the power, electrical, and life support systems. While NASA engineers quickly determined that air, water, and electricity did not exist in the Command Module sufficient to sustain the three astronauts until they could return to Earth, they found that the Lunar Module (LM)—a self-contained spacecraft unaffected by the accident—could be used as a "lifeboat" to provide austere life support for the return trip. It was a close-run thing, but the crew returned safely on 17 April 1970. The near disaster served several important purposes for the civil space program, especially prompting reconsideration of the propriety of the whole effort while also solidifying in the popular mind NASA's technological genius, since they were able to bring the crew back alive.

The third critical piece of hardware for Apollo was the Lunar Module (LM). Begun a year later than it should have been in 1962, the LM was consistently behind schedule and over budget. Nicknamed "Spider" because of its spindly legs, much of the LM's problem turned on the demands of devising two separate spacecraft components—one for descent to the Moon and one for ascent back to the Command Module—that only maneuvered outside an atmosphere. Both engines had to work perfectly, or the very real possibility existed that the astronauts would not return home. Guidance, maneuverability, and spacecraft control also caused no end of headaches. The landing structure likewise presented problems; it had to be light and sturdy and shock resistant. An ungainly vehicle emerged, which two astronauts could fly while standing. In November 1962 Grumman Aerospace Corp. signed a contract with NASA to produce the LM, and work on it began in earnest. With difficulty, the LM was orbited on a Saturn V test launch in January 1968 and judged ready for operation.

The LM proved its mettle during the first two piloted test flights and the landings of the first two Apollo missions on the lunar surface. During Apollo 9, 3–13 March 1969, the crew tested the LM in Earth orbit; and on Apollo 10, 18–26 May 1969, the LM performed well in lunar orbit, going as close to the surface as 8.5 nautical miles. It further performed well in the landing of Apollo 11 on the lunar surface on 20 July 1969, when astronaut Neil Armstrong took the controls during descent to the surface of the Moon to avoid a rock-strewn landscape and safely land in the Sea of Tranquility. While nearly running out of fuel during this maneuver, Armstrong also proved inadvertently the capability of the Apollo landing craft. Astronaut Pete Conrad did the same in December 1969 when he landed the Apollo 12 craft within approximately 160 meters of the Surveyor 3 soft lander that had been on the lunar surface since 1966. Conrad and fellow astronaut Alan Bean moonwalked over and retrieved several pieces from the spacecraft, including its television camera and some associated electrical cables, the sample scoop, and two pieces of generic aluminum tubing. As an exercise in precision landing, this mission demonstrated beyond all doubt that the LM, coupled with the skill of its pilot, was an impressive vehicle.

Achieving the Lunar Landings

The actual Apollo flight program was conducted between October 1968 and December 1972. During that period, NASA undertook two flights of program hardware in Earth orbit (Apollo 7 and Apollo 9), three circumlunar flights (Apollo 8, Apollo 10, and Apollo 13—although the latter had been intended as a landing mission), and six landing missions (Apollo 11, Apollo 12, Apollo 14, Apollo 15, Apollo 16, and Apollo 17).

No doubt the first Moon landing mission was the most significant. The crew of Neil A. Armstrong, Edwin E. (later formally changed to Buzz) Aldrin, and Michael Collins prepared to make Apollo 11 a success, in the process achieving the payoff for a program that had consumed NASA since 1961. Neil Armstrong was an inspired choice by Robert Gilruth and Deke Slayton to command that first Moon landing mission. He served in the Navy in the Korean War and then went on to work at the NACA as an engineer, research pilot, astronaut, and administrator. He famously flew the X-15 in the early 1960s before transitioning in 1962 to the astronaut corps and flying on Gemini VIII and Apollo 11. He sought neither fame nor riches, and he was always more comfortable with a small group of friends rather than the limelight before millions. When he might have done anything he wished after his completion of the Apollo 11 Moon landing mission, Armstrong chose to teach aerospace engineering at the University of Cincinnati. He lived a life of quiet honor and dignity until his passing in 2012.

Armstrong served well in commanding two other crewmates effectively. He was able to get the best out of the brilliant, temperamental, and judgmental Aldrin when so many others abhorred his personality. For all that has passed since the Apollo 11 mission concerning Aldrin—his alcohol addiction and grating personality—it is important to remember his skills in spacecraft rendezvous and spacewalking that helped to make possible that first Moon landing. The even-keeled Michael Collins rounded out the crew. In addition to his skills as a flier, he had the heart of a poet and better than any other astronaut captured the essence of space exploration. No one can read his 1974 memoir, *Carrying the Fire*, without gaining a supreme sense of gratitude for Collins's competence, honor, and self-reflectiveness.

Launched on 16 July 1969, Apollo 11 made its three-day journey to the Moon without serious incident. As commander of Apollo 11, Armstrong gained the distinction of being the first person to set foot on the Moon's surface. His words are immortal: "That's one small step for [a] man, one giant leap for mankind."

This landing completed the difficult task taken on by NASA in 1961. With the safe return of Apollo 11 to Earth on 24 July, Mission Control in Houston flashed the words of President Kennedy announcing the Apollo

Figure 6-4. One of the iconic images from the Apollo program is this photograph of Buzz Aldrin on the lunar surface during the 20 July 1969 surface operations as part of the Apollo 11 mission. It has been reproduced in many forms and for divergent purposes literally around the world. Seen in the foreground is the leg of the Lunar Module Eagle during the Apollo 11 extravehicular activity. Astronaut Neil A. Armstrong, commander, took this photograph, and his image is reflected in the visor of Aldrin's spacesuit. (NASA, AS11-40-5903)

commitment on its big screen. Those phrases were followed with these: "TASK ACCOMPLISHED, July 1969." No greater understatement could probably have been made. Any assessment of Apollo that does not recognize the accomplishment of landing an American on the Moon and safely returning before the end of the 1960s is incomplete and inaccurate.

No question, the Moon landing unified a nation divided by political, social, racial, and economic tensions for a brief moment in the summer of 1969. Virtually everyone old enough recalls where they were when Apollo 11 touched down on the lunar surface. Millions identified with Neil Armstrong as he reached the "magnificent desolation" of the Moon. "One small step," hardly; Neil Armstrong nailed it with the second phrase of his famous statement, "one giant leap for mankind."

Most of humanity gloried in the achievement, as everyone shared in the joy of the astronauts. The front pages of newspapers everywhere suggested how strong the enthusiasm was, if only momentarily. NASA estimated that because of nearly worldwide radio and television coverage, more than half the population of the planet was aware in real time of the events of Apollo 11. Although the Soviet Union tried to jam Voice of America radio broadcasts, most living there and in other countries learned about the adventure and followed it carefully. Police reports noted that streets in many cities were eerily quiet during that first moonwalk, as residents watched television coverage in homes, bars, and other public places.

Official congratulations poured in to the U.S. President from other heads of state, even as informal ones went to NASA and the astronauts. All nations having regular diplomatic relations with the United States sent their best wishes in recognition of the success of the mission. Those without diplomatic relations with the United States, such as the People's Republic of China, made no formal statement on the Apollo 11 flight, and the mission was reported only sporadically by its news media because Mao Zedong refused to publicize successes by Cold War rivals. It was not until February 1972, when Nixon flew to China and met with Mao Zedong, that the United States established formal diplomatic relations with the nation.

In all, NASA astronauts landed on the Moon six times. It was a remarkable set of accomplishments, but not to be remembered as a triumph of any one person, nation, or even NASA as a whole. Neil Armstrong always insisted that it was the result of the labor of hundreds of thousands and the accomplishment of a generation of humanity. The Apollo 11 mission engendered goodwill around the globe. "This is the greatest week in the history of the world since Creation," President Richard M. Nixon gushed in an obvious overstatement upon talking with the Apollo 11 crew when they returned from the Moon.[16] Thomas Murphy was more reasoned in a 1972 assessment: "NASA's effective implementation of the Apollo mission shows that anything we set our minds to can be done, provided all the conditions are met. Unfortunately, there will be few areas in American life where such will be the case. Nevertheless, Apollo will serve as an everlasting precedent to which optimists will be able to point."[17]

Apollo and American Race Relations

Without question, the great American original sin is the tragedy of slavery and race relations. The space program also had a role in coming to grips with this during the Apollo effort to reach the Moon. Throughout the decade there were fewer than 3 percent of the NASA professional workforce that were African Americans or other people of color. There were virtually none at NASA facilities in the South. For example, African Americans comprised 18 percent of Huntsville, Alabama's, population throughout much of the 1960s, but less than 1 percent of Marshall Space Flight Center's workforce. After the 1963 Birmingham bombing and riots, the Kennedy administration made addressing this disparity a moral imperative.

NASA Administrator James E. Webb stepped out to push for more action from all of his Center Directors, but especially from Wernher von Braun in Huntsville. At Webb's insistence, on 18 June 1963, representatives from NASA and other federal entities in Huntsville met and decided to conduct surveys of housing and federal employment practices, to assist Alabama A&M College and Tuskegee Institute in placing African American engineers at NASA, to push contractors to ensure equal employment opportunity, and to increase African American employment in all arenas. Marshall Space Flight Center then established an Affirmative Action Program, hiring Dr. Frank R. Albert to coordinate it.

With the passage of the Civil Rights Act in 1964 and the Voting Rights Act in 1965, the Johnson administration pressed every federal agency—as well as government contractors and other entities—to adhere to this new law. James Webb—as a loyal Johnson supporter if for no other reason—led the charge in NASA to press for more minority hiring, especially of engineers and scientists rather than other staff. These efforts were only moderately successful.

With the many key facilities belonging to NASA located in the southern United States, where racial segregation was still in place, it was difficult to recruit mathematicians, engineers, scientists, and technicians of color throughout the decade. Julius Montgomery, Clyde Foster, and a few other African American engineers that came to NASA's Kennedy Space Center, Florida, and Marshall Space Flight Center, Alabama, in the mid-1960s were notable exceptions. Whether they liked it or not, Foster, Montgomery, and others represented a vanguard of the growing movement toward greater diversity at NASA. Some African American women, furthermore, served important roles in the Apollo program. Among the most famous was Katherine Johnson, a woman of color whose career began at the Langley Research Center in 1953. After the facility was absorbed into NASA in 1958, Johnson was recruited to work on rocket trajectories for Project Mercury. She went on to make further significant contributions to the space agency's work until her retirement in 1986.

NASA's relatively poor showing on minority employment was even more on view concerning the astronaut corps. None were African Americans. It might have been otherwise. In 1963 United States Air Force pilot Captain Edward Dwight, Jr., became the first astronaut trainee of color, but for a military program, which catapulted him to instant fame. He was featured in news magazines around the world and on the cover of a variety of publications aimed at a black readership in the United States, such as *Ebony* and *Jet*. However, he faced severe discrimination from many of his fellow trainees as well as from government officials, which eventually prompted him to resign from the Air Force. Thereafter, the Air Force selected Major Robert Lawrence to join its military astronaut program, but he died soon after in an aircraft training accident. It would take another 11 years before NASA recruited its first African American astronaut, Guion "Guy" Bluford, who flew on Space Shuttle Challenger on 30 August 1983. Astronauts from other ethnic minorities would follow, but none were engaged in Apollo.

At the time of Apollo 11, the Reverend Ralph Abernathy, successor to Martin Luther King as head of the Southern Christian Leadership Conference, protested the launch to call attention to the plight of the poor—most of whom were African American—in the United States. He and 500 marchers of the Poor People's Campaign arrived at the Kennedy Space Center to contest the priority of the Moon launch in a nation of stark economic disparities. As Hosea Williams said at the time, "We do not oppose the Moon shot. Our purpose is to protest America's inability to choose human priorities."[18]

Abernathy asked to meet with the NASA leadership, and Thomas O. Paine, successor to James Webb, did so the day before the launch. Abernathy said that he had three requests for NASA, that some of his group be allowed to view the launch, that NASA "support the movement to combat the nation's poverty, hunger and other social problems," and that NASA's technical personnel undertake efforts "to tackle the problem of hunger." Paine responded: "if we could solve the problems of poverty in the United States by not pushing the button to launch men to the moon tomorrow, then we would not push that button." But he could not, although he promised to lead NASA as Abernathy asked. Paine also asked Abernathy to pray for the safety of the Apollo 11 crew and invited a delegation of protestors to view the launch of Apollo 11 to the Moon the next day.[19]

This interchange pointed up many inequalities in 1960s America, but it also highlighted the challenges for NASA in terms of race relations. The space agency always trailed the nation as a whole in efforts for greater equality.

Complying with federal law, the Agency established in September 1971 an Equal Employment Opportunity office at NASA Headquarters. Its head, Ruth Bates Harris, pushed hard for more equitable hiring practices and efforts to create a successful program. Harris faced an agency that had only 5 percent workforce diversity, the lowest of all federal agencies, and little interest in making changes. That diversity was even less in science and engineering positions, only 4.5 percent of the space agency by 1975. Doing battle, Harris soon found herself out of a job. Lawsuits followed, and only through years of effort did this situation become somewhat better. It took years of effort thereafter to make much headway, and while this situation has gotten somewhat better over time, NASA still has this same problem in the 21st century.

Apollo-Soyuz Test Project: A Diplomatic Success Story

The Apollo-Soyuz Test Project was purely and simply a diplomatic mission. In that sense, it was a great success. It was the first international human spaceflight, taking place at the height of the rapprochement between the United States and the Soviet Union in 1975. While it specifically tested the technologies of rendezvous and docking systems for American and Soviet spacecraft to operate together, its fundamental purpose was to walk back from the abyss of nuclear annihilation and find a path for engagement between the superpower rivals of the Cold War. If it worked out, perhaps the United States and the U.S.S.R. could undertake international space rescue as well as future joint piloted flights. The Americans used Apollo spacecraft nearly identical to the ones that orbited the Moon and later carried astronauts to Skylab, while the Soyuz craft was the primary Soviet vehicle used for cosmonaut flight since its introduction in 1967. A universal docking module was designed and constructed by NASA to serve as an airlock and transfer corridor between the two craft.

The actual flight took place between 15 and 24 July 1975, when astronauts Thomas P. Stafford, Vance D. Brand, and Donald K. Slayton took off from Kennedy Space Center to meet the already orbiting Soyuz spacecraft. Some 45 hours later, the two craft rendezvoused and docked, and then Apollo and Soyuz crews conducted a variety of experiments over a two-day period. After separation, the Apollo vehicle remained in space an additional six days while Soyuz returned to Earth approximately 43 hours after separation. The flight was more a symbol of the lessening of tensions between the two superpowers than a significant scientific endeavor, turning 180 degrees the competition for international prestige that had fueled much of the space activities of both nations since the late 1950s.

Legacies

Despite difficulties, there is no question that the success of Project Apollo in the 1960s created a public perception of NASA's culture of competence. It suggested that anything the American people pursue, and sacrifice to attain, is achievable. This is something that almost sounds unthinkable in the early 21st century, but such was indeed the case in the 1960s.

Recollections of the Apollo program's technology lead many to express wonder at the sophistication of the technical competence that made the Moon landings possible and the genius of those that built the rockets and spacecraft that carried Americans into space. Farouk el-Baz, a scientist who worked on the program, expressed well this sense of awe at the Moon landings: "Oh, the Apollo program! It was a unique effort all together. When I think about it some 40 years later, I still look at that time with wonder." He bemoans that "the Apollo spirit of innovation and can-do attitude did not last long."[20]

For the generation of Americans who grew up during the 1960s watching NASA astronauts fly into space, beginning with 15-minute suborbital trajectories and culminating in an 8-day trip to the Moon, Project Apollo signaled in a very public manner how well the nation could do when it set its mind to it. Television coverage of real space adventures was long and intense, the stakes high, and the risks of life enormous. There were moments of both great danger and high anxiety. In the whole decade, however, NASA lost not a single astronaut during a spaceflight. The civilian space agency established a reputation as a government organization that could take on difficult tasks and get them done. More difficult was ensuring that those technological skills were effectively managed and used. That NASA succeeded in doing so was critical to the fostering of a culture of competence.

The data collected about the Moon and the origins of the solar system through Apollo revolutionized knowledge of the cosmos. What NASA did not recognize until it happened was that it also revolutionized understandings about Earth. The "Earthrise" photograph taken from lunar orbit during Apollo 8 is a case in point. It fundamentally forced all peoples of the world to view the planet Earth in a new way. On its outward voyage, the Apollo 8 crew focused a portable television camera on Earth, and for the first time, humanity saw its home from afar, a tiny, lovely, and fragile "blue marble" hanging in the blackness of space. When the Apollo 8 spacecraft arrived at the Moon on Christmas Eve of 1968, the image of Earth was even more strongly reinforced when the crew took images of the planet. Excuse the sexist language here, but writer Archibald MacLeish summed up the feelings of many people when he wrote at the time that "To see the Earth as it truly is, small and blue and beautiful in that eternal

Figure 6-5. "Earthrise," one of the most powerful and iconic images from the Apollo program, was taken in December 1968 during the Apollo 8 mission. This view of the rising Earth greeted the Apollo 8 astronauts as they came from behind the Moon after the first lunar orbit. Used as a symbol of the planet's fragility, it juxtaposes the grey, lifeless Moon in the foreground with the blue-and-white Earth teeming with life hanging in the blackness of space. (NASA, 68-HC-870)

silence where it floats, is to see ourselves as riders on the Earth together, brothers on that bright loveliness in the eternal cold, brothers who know now that they are truly brothers."[21]

The modern environmental movement was galvanized in part by this new perception of the planet and the need to protect it and the life that it supports. It had the most profound effect on public consciousness of any image from the lunar surface. It came to symbolize a new era of concern for the ultimate fate of the home planet. The return of the Apollo 8 capsule with the crew safely aboard signaled a major waypoint in the Apollo program. Two additional missions took place in the first part of 1969 to pave the way for a lunar landing. Apollo 9 tested the LM in Earth orbit, and Apollo 10 did the same in lunar orbit.

Americans still hearken back to that brief, bright, shining moment when the nation went to the Moon, and many want to recreate Apollo as the 21st century progresses. But the difficulty with emphasizing this legacy of accomplishment is that it recalls a time that no longer exists. Apollo was born out of Cold War rivalries long gone, and indeed they did not exist much beyond the mid-1960s. Demonstration of American technological capability is no longer compulsory, and nothing else justifies the level of resource expenditure that it required. Others have expressed a desire to recapture what may be conceived of as the can-do spirit demonstrated by the genuine accomplishment of Apollo. Despite NASA's many achievements afterward, nothing like Apollo has ever been fully realized since.

CHAPTER 7

Exploring the Cosmos

There was nothing magic about it, but the event itself transcended the hard-edged scientific and technological knowledge that made the Curiosity rover landing on Mars successful in the summer of 2012. After years of hard work and dedication, the team working on Mars Curiosity had their moment of truth about 1:30 a.m. EDT on 6 August 2012. The first data back demonstrated that the rover had reached the surface of the Red Planet safely, and the first images to reach Earth showed where Curiosity was sitting on the Gale Crater floor. It was euphoric: at Mission Control, around NASA, in numerous science centers, and in Times Square, where thousands gathered to watch the proceedings. It was a science geek's dream come true as the folks in Times Square watching on the big screen began chanting "sci-ence, sci-ence, sci-ence."[1]

Of course there was much more to do—a lot more—as Mars Curiosity began its multiyear mission to explore the Gale Crater and to climb Mount Sharp in its center. Curiosity brought to the Red Planet's surface a formidable life sciences laboratory that added critical pieces to the puzzle of that planet's formation and evolution. This rover was the first full-scale astrobiology mission to Mars since the Viking landers of 1976. It sought locations on or under the surface to discover if Mars could have supported—or might still support—life. Mars Curiosity had 10 different instruments designed to help find that answer, and although it did not definitively answer that question, it was a stunning recent example of more than six decades' worth of NASA's scientific investigation of the universe. Throughout that long history of investigations, the chant "sci-ence, sci-ence, sci-ence" is apropos.

Creating NASA's Space Science Program

When Congress established NASA in 1958, it explicitly charged the new space agency with "the expansion of human knowledge of phenomena in the atmosphere and space."[2] In fulfillment of that mandate, NASA created the Office of Space Sciences and installed as its head the respected scientist, Homer E. Newell, brought over from the Naval Research Laboratory. Newell proved an inspired choice. He had earned his Ph.D. in mathematics at the University of Wisconsin in 1940 and served as a theoretical physicist and mathematician at the Naval Research Laboratory from 1944 to 1958 and science program coordinator for Project Vanguard. For more than a decade he guided the NASA science program, establishing a Space Science Steering Committee to provide advice and technical support. Broadly based, his science directorate got some of the most prestigious scientists in the nation involved in NASA programs.

In spite of some rocky disagreements early in NASA's history, Newell cobbled together a NASA-university-industry-research institution partnership to execute a broad range of scientific activities in the 1960s. By fostering a divergence of opinion from all interested parties, Newell ensured that decisions were not only better than could be obtained by any one person but also represented a broad consensus. Through this effort Newell and his successors established a structure for space science that worked democratically even though it was far from efficient. The scientists themselves developed decadal surveys to coalesce the various priorities of the disciplines and to rank them for future implementation. These surveys, framed through a politicized process within the National Academies of Sciences, emerged for astronomy in 1964. Written by a diverse collection of scientists from a variety of institutions, with inputs from many others, it surveyed the current state of the field, identified research priorities, and made recommendations for the coming decade, hence the name.

Decadal surveys soon followed in other scientific disciplines in the latter part of the 1960s, each providing a rallying point around which the community of scientists spoke with one voice. Indeed the various "Decadals," as they quickly came to be known, served as the necessary first step in the development of initiatives to be pursued. The basic ranking of missions, projects, and programs furthered the political process as NASA pursued these initiatives. Both the White House and Congress have respected the findings of these "Decadals" and generally follow them without serious question. This has largely altered political decision-making from discussions of scientific merits by lawmakers and others without scientific credentials to acceptance of the scientific community's findings and then deliberating over funding issues. Accordingly, space science has rarely been something that has been politically sensitive, controversial, or partisan.

In these decadal surveys the scientific community came up with a recommended set of "Flagship" missions. For instance, although not called this at the time, such large-scale space science missions as the Viking program to Mars and the Voyager probes to the outer planets were flagship missions, meaning they were large, expensive, and long lasting. In the 1990s NASA officials began to use the "Flagship" rubric to characterize those costing more than $1 billion, sometimes significantly more than $1 billion. Accordingly, the Galileo mission to Jupiter and the Cassini mission to Saturn both operated as "Flagships." Numerous recommendations for additional missions have been put forward since that time. As the 21st century progresses the major Flagship missions beyond those already mentioned have coalesced around the Great Observatories program; the James Webb Space Telescope, recently launched as a follow-on to the Hubble Space Telescope; the Mars Science Laboratory (Curiosity rover) currently in operation; two outer planet missions to Europa and Titan; and a range of other proposals still in conception stage. The decadal planning effort by the science community has proven remarkably robust and successful.

Early Exploration of the Terrestrial Planets

NASA pursued an impressive research program to gather information on the inner solar system during the 1960s. Although the most significant findings of this investigation would not come until the 1970s, perhaps the "golden age" of planetary science, studies of the planets captured the imagination of many people from all types of backgrounds like nothing else save the Apollo lunar landings. For all the genuine importance of magnetospheric physics and solar studies, meteorology and plate tectonics, it was photographs of the planets and theories about the origins of the solar system that appealed to a much broader cross-section of the public. As a result, NASA had little difficulty capturing and holding a widespread interest in this aspect of the space science program.

Observation of the planets from Earth-based instruments had been going on for centuries, but the really significant contributions of the Space Age came from satellites, either probes actually sent to the planets or space-based observatories. A centerpiece of this effort was the Mariner program, originated by NASA in the early part of the 1960s to investigate the nearby planets. Overseen by JPL, satellites of this program proved enormously productive. In the summer of 1962, Mariner 2 launched toward Venus, for example, and in December it arrived at the planet, probing the clouds, estimating planetary temperatures, measuring the charged particle environment, and looking for a magnetic field similar to Earth's magnetosphere (but finding none).

In July 1965, Mariner 4 flew by Mars, taking 21 close-up pictures, and Mariner 5 visited Venus in 1967 to investigate the atmosphere. Mariners 6 and 7, launched in February and March 1969, each passed Mars about five months later, studying its atmosphere and surface to lay the groundwork for an eventual landing on the planet. Among other discoveries from these probes, they found that much of Mars was cratered almost like the Moon, that volcanoes had once been active on the planet, that the frost observed seasonally on the poles was made of carbon dioxide, and that huge plates of the Martian crust indicated considerable tectonic activity. Proposals for additional Mariner probes were also considered but, because of budgetary considerations, did not fly during the decade. These space probes, as well as others not mentioned here, accumulated volumes of data on the near planets and changed many scientific conceptions that had long held sway.

While these successes were great, all was not rosy with the politics of planetary exploration. In the summer of 1967, even as the technical abilities required to conduct an adventurous space science program were being demonstrated, the planetary science community suffered a devastating defeat in Congress and lost funding for a satellite lander to Mars. No other NASA effort but Project Apollo was more exciting than the Mars program in the middle part of the decade. The planet had long held a special attraction to Americans, so much like Earth and possibly even sustaining life, and the lander would have allowed for extended robotic exploration of the Red Planet. A projected $2 billion program, the lander was to use the Saturn V launch vehicle being developed for Apollo.

The problem revolved around the lack of consensus among scientists on the validity of the Mars initiative. Some were excited, but others thought it was too expensive and placed too many hopes on the shoulders of one project and one project manager. Without that consensus and with other national priorities for spending for "Great Society" social programs, combatting urban unrest, and supporting the military in Vietnam, the Mars lander was an easy target in Congress. It was the first space science project ever killed on Capitol Hill. The NASA Administrator, James E. Webb, frustrated by congressional action and infuriated by internal dissension among scientists, ended all work on planetary probes.

The scientific community learned a hard lesson about the pragmatic, and sometimes brutal, politics associated with the execution of "Big Science" under the suzerainty of the federal government. Most important, it realized that strife within the discipline had to be kept within the discipline to put forward a united front against the priorities of other interest groups and other government leaders and that it could minimize this public in-fighting through the use of the emerging tool of the decadal surveys. While support from the scientific community could not guarantee that any initiative would become a political reality, without it a program could not achieve funding. It also learned that while a $750 million program found little opposition at any level, a $2 billion project crossed an ill-defined but very real threshold triggering intense competition for those dollars. Having learned these lessons, as well as some more subtle ones, the space science community regrouped and went forward in the latter part of the decade with a trimmed-down Mars lander program, called Viking, which was funded and provided astounding scientific data in the mid-1970s.

Learning About Venus

Venus had long been a place of mystery for humanity; relatively close to Earth and about the same size, its clouds defeated learning much with observations from afar. In 1960, Cornell University astronomer Carl Sagan and JPL meteorologist Will Kellogg chaired a conference at Caltech aimed at identifying questions about Mars and Venus that might be answered by the first JPL planetary missions. At this point, in popular culture Venus was largely seen as a slightly warmer Earth, possibly with global jungles. A minority thesis was that it had a global ocean. In addition, many had generally assumed that Venus could have an Earth-like atmosphere, with mostly nitrogen and other trace gases in small percentages.

Perhaps there was a warm, watery world underneath the dense of clouds of Venus, possibly harboring aquatic and amphibious life. "It was reasoned that if the oceans of Venus still exist, then the Venusian clouds may be composed of water droplets," noted JPL researchers in a book produced about the forthcoming Mariner 2 mission in 1961, "if Venus were covered by water, it was suggested that it might be inhabited by Venusian equivalents of Earth's Cambrian period of 500 million years ago, and the same steamy atmosphere could be a possibility."[3]

There were some indications from radio telescope and infrared studies that suggested otherwise. Carl Sagan, then a recent graduate, argued that Venus was so hot that it could not have water or any sort of life of any type. He made his first important discovery by realizing that the greenhouse effect under the clouds of Venus could have a surface temperature of 800 degrees Fahrenheit based on radio telescope data. And he thought that a probe to Venus could decide the case one way or another. Mariner 2 in 1962 confirmed Sagan's findings. (See Figure 7-1.)

Through programs such as Mariner, an understanding of Venus emerged that demonstrated it was a very inhospitable place. Scientists also learned that Venus's atmosphere consists of approximately 97 percent carbon dioxide. And

Figure 7-1. Successful NASA missions to Venus.

1.	Mariner 2	Flyby	1962
2.	Mariner 5	Flyby	1967
3.	Mariner 10	Venus and Mercury flybys	1973–1975
4.	Pioneer Venus	Two orbiters/probes	1978–1992
5.	Magellan	Radar mapping orbiter	1989–1994
6.	Galileo	Jupiter orbiter (Venus flyby)	1990
7.	Cassini-Huygens	Saturn orbiter (Two Venus flybys)	1998–1999
8.	MESSENGER	Mercury orbiter (Two Venus flybys)	2006 and 2007
9.	Parker Solar Probe	NASA Solar Mission (Multiple Venus flybys)	2018

while it was very rocky, it had no water, and temperatures on the surface were more than 450 degrees Celsius regardless of whether it was night or day, summer or winter. Finally, the pressure on the surface of Venus is 90 times of what may be found on Earth.

Because of Venus's thick cloud cover, scientists early on advocated sending a probe with radar to map Venus. Pioneer Venus had made a start toward realizing this goal, orbiting the planet for more than a decade to complete a low-resolution radar topographic map. Likewise, the Soviets' Venera 15 and 16 missions in 1983 provided high-resolution coverage over the northern reaches of the planet.

NASA returned to Venus when the Magellan orbiter mapped Venus with imaging radar in 1990. This mission followed a Pioneer Venus 1 spacecraft that had orbited the planet throughout the 1980s, completing a low-resolution radar topographic map, and Pioneer Venus 2, which dispatched heat-resisting probes to penetrate Venus's dense clouds. It also built on the work of the Soviet Union, which had compiled radar images of the northern part of Venus and had deployed balloons into the Venusian atmosphere. Magellan arrived at Venus in September 1990 and mapped 98 percent of the surface at high resolution, parts of it in stereo. These data betrayed some surprises: among them the discovery that plate tectonics was at work on Venus and that lava flows clearly showed the evidence of volcanic activity. In 1993, at the end of its mission, scientists turned their attention to a detailed analysis of Magellan's data.

More recently, one NASA probe to Jupiter—Galileo—flew by Venus on a gravity-assist trajectory, collecting scientific data during its encounter, as did Cassini-Huygens with two flybys en route to Saturn. Lastly, MESSENGER (standing for MErcury Surface, Space ENvironment, GEochemistry, and Ranging) made two flybys of Venus en route to Mercury. In October 2006, and again in June 2007, MESSENGER passed behind Venus in a blind flyby.

Although years of research await Venus explorers from the data returned thus far, collectively they fundamentally suggest that life on Venus—at least as humans understand it—probably never existed there.

The Lure of the Red Planet

But what of Mars? It had long held a special fascination for humans who pondered the planets of the solar system—partly because of the possibility that life might either presently exist or at some time in the past have existed there—championed by gentleman astronomer Percival Lowell during the latter part of the 19th century. He built what became the Lowell Observatory near Flagstaff, Arizona, to study the planet. He argued that Mars had once been a watery planet and that the topographical features known as canals had been built by intelligent beings. The idea of intelligent life on Mars remained in the popular imagination for a long time, and only with the scientific data returned from NASA probes to the planet since the beginning of the Space Age did this begin to change.

By the latter 1960s, NASA had been successful in reaching Mars only once, with Mariner 5 in 1965. Those results had been disappointing for those who sought life on the Red Planet. *U.S. News and World Report* announced that "Mars is dead."[4] Even President Lyndon Johnson pronounced that "life as we know it with its humanity is more unique than many have thought" because of the imagery from Mariner 5. Mariner 6 and Mariner 7, launched in February and March 1969, each passed Mars in August 1969, studying its atmosphere and surface to lay the groundwork for an eventual landing on the planet.[5] Their pictures verified the Moon-like appearance of Mars and gave no hint that Mars had ever been able to support life.

There was still hope, however, and the search for signs of life prompted emphasis on the exploration of Mars. NASA Administrator James C. Fletcher, for example, commented on this possibility in 1975:

> Although the discoveries we shall make on our neighboring worlds will revolutionize our knowledge of the Universe, and probably transform human society, it is unlikely that we will find intelligent life on the other planets of our Sun. Yet, it is likely we would find it among the stars of the galaxy, and that is reason enough to initiate the quest.... We should begin to listen to other civilizations in the galaxy. It must be full of voices, calling from star to star in a myriad of tongues. Though we are separate from this cosmic conversation by light years, we can certainly listen ten million times further than we can travel....[6]

It is hard to imagine anything more important than contacting another intelligent race. It could be the most significant achievement of this millennium, perhaps the key to our survival as a species.

Despite delays, Project Viking represented the culmination of a series of exploratory missions that had begun in 1964 with Mariner 4 and continued with Mariner 6 and Mariner 7 flybys in 1969 and a Mariner 9 orbital mission in 1971 and 1972. The Viking mission used two identical spacecraft, each consisting of a lander and an orbiter. Launched in August 1975, Viking 1 spent nearly a year cruising to Mars, placed an orbiter in operation around the planet, and landed on 20 July 1976, on the Chryse Planitia (Golden Plains). Viking 2 was launched in September 1975 and landed on 3 September 1976. The Viking project's primary mission ended on 15 November 1976, although the spacecraft continued to operate for six years after first reaching Mars. The last transmission from the planet reached Earth on 11 November 1982.

One of the most important scientific activities of this project involved an attempt to determine whether there was life on Mars. Although the three biology experiments discovered unexpected and enigmatic chemical activity in the Martian soil, they provided no clear evidence for the presence of living microorganisms in soil near the landing sites. According to mission biologists, Mars was self-sterilizing. They concluded that the combination of solar ultraviolet radiation that saturates the surface, the extreme dryness of the soil, and the oxidizing nature of the soil chemistry had prevented the formation of living organisms in the Martian soil. However, the question of life on Mars at some time in the distant past remains open.

The uncertainty of the conclusions from Viking haunted the program's chief scientist, Gerald Soffen, ever after. He was known to second-guess his judgment; perhaps he should have installed a microscope on the lander. But he also believed he did the best he could. "I think what we did was ahead of our time. We were young enough not to know that it couldn't be done," Soffen recalled.[7]

Viking found no evidence of surface life, or even life that might live at the depths that the lander could dig on the Martian surface, but as it turns out that should not have been surprising. Surface dwellers are probably rare. On Earth, most of the biomass lives below the planetary surface in the soil or the oceans. Regardless of negative results from the Viking landers, this fact offered something for scientists to cling to as they considered future exploration of the Red Planet.

The failure of Viking to find evidence of life on Mars revealed a core problem of overselling possibilities for extraterrestrial life and its discovery. Thereafter, no spacecraft reached Mars for more than 20 years after Viking (Figure 7-2).

Figure 7-2. Successful NASA missions to Mars.

1.	Mariner 4	Flyby	1964
2.	Mariner 6	Flyby	1969
3.	Mariner 7	Flyby	1969
4.	Mariner 9	Orbiter	1971
5.	Viking 1 and 2	Orbiters/landers	1975
6.	Mars Global Surveyor	Orbiter	1996
7.	Mars Pathfinder	Lander and rover	1996
8.	Mars Odyssey	Orbiter	2001
9.	Spirit and Opportunity (Mars Exploration Rovers)	Two rovers	2003
10.	Mars Reconnaissance Orbiter	Orbiter	2005
11.	Phoenix Mars Lander	Lander	2007
12.	Curiosity (Mars Science Laboratory)	Rover	2011
13.	MAVEN	Orbiter	2013
14.	InSight	Lander	2018
15.	Perseverance	Rover	2021

A change to the beliefs in life on Mars took place in August 1996 when a team of NASA and Stanford University scientists announced that a Mars meteorite found in Antarctica contained possible evidence of ancient Martian life. When the 2-kilogram (4.2-pound), potato-sized rock, identified as ALH84001, formed as an igneous substance about 4.5 billion years ago, Mars was much warmer and probably contained oceans hospitable to life. Then, about 15 million years ago, a large asteroid hit the Red Planet and jettisoned the rock into space, where it remained until it crashed into Antarctica about 11,000 B.C.E. The scientists presented three intriguing, but not conclusive, pieces of evidence that suggest that fossil-like remains of Martian microorganisms, which date back 3.6 billion years, are present in ALH84001. While scientists proved the initial findings of the NASA researchers wrong, this investigation led to added support for an aggressive set of missions to Mars.

Mars exploration received an additional impetus on 4 July 1997, when Mars Pathfinder successfully landed on Mars, the first landing on the Red Planet since 1976. Its small, 23-pound robotic rover, named Sojourner, departed the main lander and began to record weather patterns, atmospheric opacity, and the chemical composition of rocks washed down into the Ares Vallis plain, which looked for all the world like an ancient, flooded landscape in Mars's northern hemisphere. This vehicle completed its projected milestone 30-day mission on 3 August 1997, capturing far more data on the atmosphere, weather, and geology of Mars than scientists had expected. In all, the Pathfinder mission returned more than 1.2 gigabits (1.2 billion bits) of data and over 10,000 tantalizing pictures of the Martian landscape.

A new portrait of the Martian environment emerged thereafter. Pathfinder's discoveries, coupled with those of other Mars probes, suggested that Mars was once a watery planet. Since liquid water is the fundamental building block of life on this planet, its presence on Mars portended unique new opportunities to determine if life had ever existed there. NASA developed the strategy for Mars exploration built upon the motto, "Follow the Water." Accordingly, NASA's strategy would be to seek liquid water, probably deep beneath the surface. An orbiter, Mars Global Surveyor, reached the planet in 1998 and offered titillating hints of water. At a June 2000 press conference, NASA unveiled more than 150 geographic features all over Mars probably created by fast-flowing water. These data, and others captured by other space probes, led scientists to theorize that billions of years ago, Earth and Mars might have been remarkably similar places.

The missions of the twin Mars Exploration Rovers, Spirit and Opportunity, which reached the surface in 2004, added to the already compelling evidence that life probably once existed on Mars. Spirit explored the Gusev Crater and revealed a basaltic setting, one not greatly suggestive of past water on Mars. It became stuck in soft soil in 2009, and the next year NASA lost contact with it.

Opportunity had early success by landing close to a thin outcrop of rocks that lent itself to an analysis confirming that a body of salty water once flowed gently over the area. Opportunity found sands that were reworked by water and wind, solidified into rock, and soaked by groundwater. It continued to examine more sedimentary bedrock outcroppings where an even broader, deeper section of layered rock revealed new aspects of Martian geologic history. Once again, scientific analysis on Earth pointed to a past environment that could have been hospitable to life and also could have fossil evidence preserved in it. Opportunity remained operational until 10 June 2018, one of the astounding accomplishments in Mars exploration.

Despite the success of these efforts, exploring Mars proved an exceptionally difficult challenge in the latter 1990s. It is at least an order of magnitude greater in complexity, risk, and cost than voyages to the Moon. In the 20th century, NASA scientists succeeded in placing only three robotic spacecraft on the surface of Mars. Two NASA missions in 1999, Mars Polar Lander and Mars Climate Orbiter, crashed. Soviet scientists sent seven landers to Mars and failed each time. Of the 29 missions sent to Mars during the 20th century only 10 were fully successful, a 62 percent failure rate. Mars, it seems, eats spacecraft.

Figure 7-3. The twin rovers of the Mars Exploration Rover mission pose in 2003 just before launch to the Red Planet with their innovative predecessor, the flight spare of the Sojourner rover from NASA's 1997 Pathfinder mission. (NASA, PIA04422)

No less significant, in August 2012, NASA landed Curiosity, the Mars Science Laboratory, on Mars. Since landing, Curiosity has made some stunning discoveries. For example, in measuring radiation levels on the surface of the Red Planet, it has found that Martian radiation levels are comparable to those experienced by astronauts aboard the International Space Station. This enhances the possibility that human activities on the surface are possible. Additionally, Curiosity has found beyond any real doubt that there is an ancient streambed where water once flowed roughly knee-deep for thousands of years at a time. In drilling into the soil, Curiosity also spotted some of the key chemical ingredients for life.

Follow-on missions have been conducted since that time. Launched in 2013, the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission explicitly undertook investigations of the planet's upper atmosphere and space environment to ascertain what might have happened to Mars's atmosphere and climate over its history. NASA's Interior exploration using Seismic Investigations, Geodesy, and Heat Transfer (InSight) lander reached Mars on 26 November 2018, with the intention of illuminating processes deep under the planet's surface. Just recently, NASA's Perseverance rover reached the Martian surface on

18 February 2021 to undertake a multiyear mission to explore the Jezero Crater on the western edge of the Isidis Planitia impact basin on Mars. Carrying a unique mini-helicopter, named Ingenuity, the mission tests the possibility of extending research on Mars using low-level flying vehicles. None of these missions have yet solved the riddle of whether or not life has ever existed on Mars, but all helped establish possibilities that such may have been the case.

At present, there are a few scientists who would go so far as to theorize that perhaps some water is still present deep inside the planet. If so, microorganisms might still be living beneath Mars's polar caps or in subterranean hot springs warmed by vents from the Martian core. Scientists are quick to add, however, that these are unproven theories for which evidence has not yet been discovered.

Orbiting Mercury

While other spacecraft had flown briefly in the vicinity of Mercury, the closest planet to the Sun, not until 2004 did NASA launch the first mission to orbit and take a full measure of readings about the planet. Following a trajectory that required six planetary flybys, six propulsive maneuvers, and about six and a half years, MESSENGER (an acronym for MErcury Surface, Space ENvironment, GEochemistry, and Ranging) reached that sweltering terrestrial planet. The mission team significantly expanded the envelope of engineering practice, with the first operational demonstration of solar sailing using a large kite-like object to capture the solar wind.

Prior to the MESSENGER mission, Mercury was poorly understood, but as the nearest planet to the Sun and the smallest of the four rocky planets—Mercury, Venus, Earth, and Mars—it offered a critical anchor point for understanding the solar system. During its operation between reaching Mercury orbit on 17 March 2011 and the end of the program on 30 April 2015, MESSENGER's science team found a number of surprising results, including flooding and explosive volcanism in early Mercury history, contraction of planetary geology on a global scale, a magnetic dipole aligned with the planet's spin axis, 60 to 70 percent iron contained in the planet's interior, and compelling support for the hypothesis that Mercury harbors abundant water ice and other frozen volatile materials in its permanently shadowed polar craters.

Reconnoitering the Outer Solar System

As NASA pursued science missions in the 1970s, it seized an opportunity available every 176 years when gas giants in the outer solar system gathered on one side of the Sun. This geometric lineup made possible close-up observation of these giants on a single mission, the so-called Grand Tour. The flyby of each planet would bend the spacecraft's flightpath and increase its velocity enough to deliver it to the next destination. This would occur through a complicated process known as "gravity assist," something like a slingshot effect, whereby the flight time to Neptune could be reduced from 30 to 12 years.

To prepare the way for the Grand Tour, in 1964 NASA conceived Pioneer 10 and 11 as outer solar system probes. Although severe budgetary constraints prevented starting the project until the fall of 1968 and forced a somewhat less ambitious effort, Pioneer 10 was launched on 3 March 1972. It arrived at Jupiter on the night of 3 December 1973, and although many were concerned that the spacecraft might be damaged by intense radiation discovered in Jupiter's orbital plane, the spacecraft survived, transmitted data about the planet, and continued on its way out of the solar system.

In 1973 NASA launched Pioneer 11, providing scientists with their first close-up view of Jupiter. The close approach and the spacecraft's speed of 107,373 mph, by far the fastest speed ever reached by an object launched from Earth, hurled Pioneer 11 1.5 billion miles across the solar system toward Saturn, encountering the planet's south pole within 26,600 miles of its cloud tops in December 1974. In 1990, Pioneer 11 officially departed the solar system by passing beyond Pluto and headed into interstellar space toward the center of the Milky Way galaxy. Pioneer 11 ended its mission 30 September 1995, when the last transmission from the spacecraft was received.

NASA received Pioneer 10's last, very weak signal on 22 January 2003. At last contact, Pioneer 10 was 7.6 billion miles from Earth, or 82 times the nominal distance between the Sun and Earth. At that distance, it takes more than 11 hours, 20 minutes for the radio signal, traveling at the speed of light, to reach Earth. It will continue to coast silently as a ghost ship into interstellar space, heading generally for the red star Aldebaran, which forms the eye of the constellation Taurus (The Bull). Aldebaran is about 68 light-years away. It will take Pioneer 10 more than 2 million years to reach it. "From Ames Research Center and the Pioneer Project, we send our thanks to the many people at the Deep Space Network (DSN) and the Jet Propulsion Laboratory (JPL), who made it possible to hear the spacecraft signal for this long," said Pioneer 10 Flight Director David Lozier at the time of the last contact.[8]

Both Pioneer 10 and 11 were remarkable space probes, stretching from a 30-month design life cycle into a mission of more than 20 years and returning useful data not just about the Jovian planets of the solar system but also about some of the mysteries of the interstellar universe.

Meanwhile, NASA technicians prepared to launch what became known as Voyager to perform flybys of Jupiter, Saturn, Uranus, and Neptune. Even though the four-planet mission was known to be possible, NASA found it soon became too expensive to build a spacecraft that could go the distance, carry the instruments needed, and last long enough to accomplish such an extended mission. Thus, the two Voyager spacecraft were funded to conduct intensive flyby studies only of Jupiter and Saturn, in effect repeating on a more elaborate scale the flights of the two Pioneers. Nonetheless, the engineers designed as much longevity into the two Voyagers as the $865 million budget would allow. NASA launched them from the Kennedy Space Center, Florida: Voyager 2 lifted off on 20 August 1977, and Voyager 1 entered space on a faster, shorter trajectory on 5 September 1977.

As the mission progressed, with the successful achievement of all its objectives at Jupiter and Saturn in December 1980, additional flybys of the two outermost giant planets, Uranus and Neptune, proved possible—and irresistible—to mission scientists and engineers at JPL in Pasadena, California. Accordingly, as the spacecraft flew across the solar system, remote-control reprogramming was used to recalibrate the Voyagers for the greater mission.

The two spacecraft returned to Earth information that has revolutionized the science of planetary astronomy, helping to resolve some key questions while raising intriguing new ones about the origin and evolution of the planets in this solar system. The two Voyagers took well over 100,000 images of the outer planets, rings, and satellites, as well as millions of magnetic, chemical spectra, and radiation measurements. They discovered rings around Jupiter, volcanoes on Io, shepherding satellites in Saturn's rings, new moons around Uranus and Neptune, and geysers on Triton. The last imaging sequence was Voyager 1's portrait of most of the solar system, showing Earth and six other planets as sparks in a dark sky lit by a single bright star, the Sun.

At the dawn of the 21st century, both Voyagers continued to provide important scientific data about the heliosheath and heliopause, where the flow of the solar wind eventually stops as it plows into the particles and atoms from other stars embedded in the magnetic field of our galaxy.

On 3 December 2012, Voyager project scientist Edward C. Stone and his colleagues Stamatios Krimigis and Leonard Burlaga stated in a NASA press conference: "Voyager has discovered a new region of the heliosphere that we had not realized was there. We're still inside, apparently. But the magnetic field now is connected to the outside. So it's like a highway letting particles in and out."[9]

Following on the Voyager mission, sustained exploration of Jupiter commenced on 18 October 1989, when NASA deployed the Galileo spacecraft from a Space Shuttle mission, STS-34, and set it on a gravity-assisted journey to

Jupiter, arriving in December 1995. The first spacecraft to orbit the giant planet, Galileo had to fly by both Venus and Earth and made the first close flyby of asteroid Gaspra in 1991, providing scientific data on all. This began a two-year encounter with the planet in which Galileo sent back to Earth scientific data about the density and chemical makeup of the giant planet's cloud cover.

Prior to reaching its destination in 1995, Galileo had become a source of great concern for both NASA and public officials because not all of its systems were working properly (i.e., its large high-gain telecommunications antenna failed to unfurl as intended), but once it arrived at Jupiter and carried on its mission through 2003, it returned enormously significant scientific data including evidence of subcrustal oceans on Europa, Jupiter's large ice-rock moon.

Among Galileo's other successes was capturing imagery of comet Shoemaker-Levy 9's collision with Jupiter in July 1994, discovering a turbulent Jovian atmosphere, complete with lightning and thunderstorms a thousand times the size of those on Earth, and conducting close-up inspections of the Jovian moons Ganymede, Callisto, and Io. While passing by the latter moon, Galileo observed eruptions of Io's Loki volcano, the largest and most powerful in the solar system. Galileo also sent a probe into Jupiter's atmosphere; its findings, writes historian Michael Meltzer, "made it necessary for scientists to revisit many of their beliefs about the formation and evolution of our solar system's giant gaseous planets. Measurements of atmospheric composition, wind velocities, temperatures, cloud characteristics, electrical storms, and elemental and molecular abundances painted a hugely different picture of Jupiter from what was expected."[10]

In mid-1995, Galileo deployed the probe that would parachute into Jupiter's dense atmosphere. The two spacecraft then flew in formation the rest of the way to Jupiter; while the probe began its descent into the planet's atmosphere, the main spacecraft went into a trajectory that placed it in a near-circular orbit. On 7 December 1995, the probe began its descent. Its instruments began relaying back data to the orbiter on the chemical composition of the atmosphere, the nature of the cloud particles and structure of the cloud layers, the atmosphere's radiative heat balance and pressure and dynamics, and the ionosphere. The probe lasted for about 45 minutes before the atmosphere and the pressure of the planet destroyed it. During that time, the orbiter stored the returned data. With the high-gain antenna being inoperative, it took months for the scientists and technicians to coax the data back to Earth for analysis.

In 1996, data from Galileo revealed that Jupiter's moon, Europa, may harbor "warm ice" or even liquid water—key elements in life-sustaining environments. Many scientists and science fiction writers have speculated that Europa—in addition to Mars and Saturn's moon Titan—is one of the three planetary bodies in this solar system that might possess, or may have possessed, an environment where primitive life could exist. This proved one of the astounding scientific discoveries of the 1990s and prompted scientists to advocate sending a lander to explore Europa.

The flight team for Galileo ceased operations on 28 February 2003, after a final playback of scientific data from the robotic explorer's tape recorder. The team then prepared commands for the spacecraft's on-board computer to manage the remainder of its life. Galileo coasted for the next seven months before taking a 21 September 2003 plunge into Jupiter's atmosphere, thereby ending what had been a remarkably successful mission.

Representing the international character of many NASA outer planetary missions, Cassini-Huygens was a joint effort of NASA, the European Space Agency, and the Italian Space Agency and has also proved to be an incredible success. Launched in 1997, it arrived at Saturn and began orbiting the planet on 1 July 2004. It also sent a probe (Huygens) to the surface of Saturn's moon Titan on 15 January 2005. Huygens was a product of the European Space Agency and the first outer planetary mission by that organization.

At Saturn, Cassini discovered three new moons (Methone, Pallene, and Polydeuces), observed water ice geysers erupting from the south pole of the moon Enceladus, obtained images appearing to show lakes of liquid hydrocarbon (such as methane and ethane) in Titan's northern latitudes, and discovered a storm at the south pole of Saturn with a distinct eye wall. Cassini, like Galileo at Jupiter, has demonstrated that icy moons orbiting gas giant planets are potential refuges of life and attractive destinations for a new era of robotic planetary exploration. In addition, on 3 April 2014, NASA reported that Cassini had found evidence of a large subterranean water ocean on Enceladus, one of Saturn's moons. It was yet another instance of a possible abode of life in the solar system.

Finally, NASA has sent the New Horizons spacecraft to Pluto and the Kuiper Belt, a region of smaller bodies in the outer solar system. The Kuiper Belt remained theory until the 1992 detection of a 150-mile-wide body, called 1992QB1, located at the distance of the suspected belt. Several similar-sized objects were discovered thereafter, confirming that the belt of icy objects astronomers had predicted did indeed exist. The planet Pluto, discovered in 1930 by Clyde Tombaugh, is only the largest member of the Kuiper Belt. Moreover, Pluto's largest moon, Charon, is half the size of Pluto, and the two form a binary planet, whose gravitational balance point is between the two bodies. Other named objects soon joined Pluto, including 1992 QB_1, Orcus, Quaoar, Ixion, 90377 Sedna, and Varuna.

The discovery of these many objects, nearly as large as Pluto, led the International Astronomical Union (IAU) in 2006 to reclassify Pluto from a planet—there would henceforth be eight of them in our solar system—to the new designation of "dwarf planet." The first members of the "dwarf planet" category were Ceres, Pluto, and 2003 UB_{313}. The IAU also specifically commented that "dwarf planet" status of Pluto would hereafter be recognized as a critical prototype of a new class of trans-Neptunian objects. While this decision remains controversial, it represents an important recent step in understanding the origins and evolution of the solar system.

Since no planetary spacecraft had previously been sent to Pluto or the Kuiper Belt, when launched on 19 January 2006, New Horizons caused an uproar in public interest when it reached Pluto. On 14 July 2015, New Horizons passed Pluto at a distance of only 6,200 miles (10,000 km). Soon after, it passed within 16,000 miles (27,000 km) of Charon. The probe continued to observe the two bodies through mid-August 2015, and also found a second moon. Because of the long time lag between collecting and sending data back to Earth, it took until mid-April 2016 for NASA mission controllers to receive the last of the data from these observations.

Passing Pluto, New Horizons began an extensive exploration of the Kuiper Belt that extends into the 2020s, involving two encounters of objects ranging from about 25–55 miles (40–90 km) in diameter. The outcome of this exploration added reams of knowledge to understandings about the outer solar system.

Implementing the Discovery Program

In 1993 NASA's Mars Observer probe failed en route to the Red Planet. Intended to provide the most detailed data yet available about Mars, the mission went smoothly until controllers lost contact with it on 21 August 1993, three days before the spacecraft's capture in orbit around Mars. The loss of the nearly $1 billion Mars Observer probably came as a result of an explosion in the fuel lines of the space vehicle.

Afterward, NASA Administrator Daniel S. Goldin declared that the space agency should never build another "Battlestar Galactica," a large, expensive space probe that is "too big to fail." This had been a longstanding problem; with every approved project, it became irresistible not to expand its capability, increasing its cost, and lengthening its schedule. Goldin insisted on a new philosophy of "faster, better, cheaper" for the Agency's space probes and advocated a mixture of large and small spacecraft to avoid the long hiatus that could occur if a mission failed.

Even before Goldin turned his attention to this problem, Dr. Wesley T. Huntress, Jr., NASA's Associate Administrator for Space Science, had inaugurated the Discovery program of relatively small space science missions.

Embracing a "faster, better, cheaper" methodology for conceiving and executing space missions, the idea was to decrease the time of designing, building, and launching new spacecraft while holding down the typically staggering costs. The science element might be more limited than most previous missions, but advocates believed NASA should be able to build and fly more probes using this approach. It proved a fortuitous strategy in many ways. While this methodology was not universally successful, the box score on these missions was some 80 percent successful, only modestly less successful than more expensive flagship projects.

Since first inaugurated, the Discovery program has flown 12 missions, with additional ones under way, beginning with the Near Earth Asteroid Rendezvous (NEAR) probe, which visited and landed on the asteroid Eros in 1996, and the wildly successful Mars Pathfinder and Sojourner rover in 1997. Other missions followed with a track record since that time of reasonable success in terms of mission capability, science delivered, and costs minimized (Figure 7-4).

Early NASA Investigations of the Universe

At the same time that these findings were fundamentally reshaping knowledge of the solar system, astronomers were investigating, and also profoundly affecting, humanity's understanding of the universe beyond. The traditional scientific field of astronomy underwent a tremendous burst of activity in the 1960s because of the ability to study the stars through new types of telescopes. In addition to greatly enhanced capabilities for observation in the visible light spectrum, NASA and other institutions supported the development of a wide range of x-ray, gamma-ray, ultraviolet, infrared, microwave, cosmic-ray, radar, and radio astronomical projects. These efforts collectively informed the most systematic efforts yet to explain the origins and development of the universe.

Space-based observatories provided an opportunity to expand far beyond the capabilities offered by ground-based observatories. Fundamental to this was the development of a series of Orbiting Astronomical Observatories (OAO), first conceptualized not long after the birth of NASA. Two of these aluminum, octagonally shaped, solar-powered spacecraft were launched during the 1960s. The first failed less than two days into its mission because of a power system failure, but with the launch of OAO 2 on 7 December 1968, the potential of the program began to pay off as it provided an abundance of information on ultraviolet, gamma-ray, x-ray, and infrared radiation; on the structure of stars; and on the distribution and density of matter in the interstellar environment. A series of six Orbiting Geophysical Observatories (OGO) also contributed to this study, as well as to the study of the solar system, by taking measurements of cosmic rays, particles, and fields in the interplanetary medium as well as radio emissions.

Figure 7-4. Completed NASA Discovery missions.

1. Near Earth Asteroid Rendezvous (NEAR)	1996–2002	Performed flyby of asteroid Mathilde in June 1997; landed on asteroid Eros in February 2001.
2. Mars Pathfinder	1996–1998	Landed on Mars, 4 July 1997; dispatched Sojourner rover and conducted studies of Ares Vallis flood plain.
3. Lunar Prospector	1998–1999	Orbited Moon; discovered evidence of water ice at the Moon's north and south poles; mission completed July 1999.
4. Stardust	1999–2011	Encountered comet Wild 2 in 2004 and returned samples of comet material to Earth in 2006.
5. Genesis	2001–2004	Collected solar wind and returned to Earth; return capsule crashed but some data still resulted.
6. Comet Nucleus Tour (CONTOUR)	2002	Failed mission to visit and study comets.
7. MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER)	2005–2015	Conducted the first orbital study of Mercury.
8. Deep Impact	2005–2013	Comet probe, impactor embedded in comet Tempel 1 on 4 July 2005. Afterward, conducted flyby of comet Hartley 2 and other bodies.
9. Dawn	2011–2018	Probe visiting protoplanet Vesta and the dwarf planet Ceres.
10. Kepler	2009–2018	Heliocentric, Earth-trailing space observatory that searched for exoplanets, especially Earth-sized planets.
11. Gravity Recovery and Interior Laboratory (GRAIL)	2011–2012	Two lunar orbiters mapping gravitational fields of the Moon to determine its interior structure.
12. Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight)	2018–Present	Mars lander studying the interior structure and composition of Mars.

One of the exciting projects in this arena was x-ray astronomy. On 12 June 1962, the first rocket was launched using instruments to detect whether or not x rays were present in any particular quadrants of the galaxy. It discovered a power source in the center. Calculations demonstrated that x-ray emissions from this source were 10 times that of the Sun. In July 1963, another instrument package sent above the atmosphere took readings of the Crab Nebula and found intense x-ray activity emanating from it. In December 1970, the x-ray observatory Uhuru mapped about 85 percent of the sky, then located and measured the intensity of 161 x-ray sources. Many of these turned out to be black holes, a significant discovery of a segment of space where mass is so compressed and gravity so great that neither matter nor light can escape. Large amounts of x rays, however, are emitted and can help explain much about the evolution of the universe.

These efforts have been ongoing since the beginnings of the Space Age and represent essential developments in understanding the universe. By the early 1970s, a wide variety of scientific fields enjoyed the yield of the research obtained from the new tools available to scientists. During the decade, two important scientific disciplines began to emerge as foremost in the field: the exploration of the solar system and the study of the universe. Throughout this era, funding for space science and applications in NASA was never more than $760 million per year (and usually much less), but the return was impressive. The quest for understanding that these efforts helped satisfy gathered momentum during the 1970s as new projects, many of them begun in the 1960s, came to fruition.

NASA's Great Observatories

In the early 1990s a new fleet of space-based astronomical observatories helped to transform astronomy through the Great Observatories program of four major space-based projects launched between 1990 and 2003. Each of these observatories was designed to conduct astronomical studies over different wavelengths (visible, gamma rays, x rays, and infrared), but when used in conjunction with each other the observatories allowed astronomers to intensely study the same object in the cosmos at divergent spectral wavelengths.

The Hubble Space Telescope

The first, and by far the most significant, of the Great Observatories was the $2 billion Hubble Space Telescope (HST) that had been launched from the Space Shuttle in April 1990. Using this telescope, NASA envisioned that scientists could gaze farther into space than ever before, viewing galaxies as far away as 15 billion light years. A key component of it was a precision-ground 94-inch primary mirror shaped to within micro inches of perfection from ultra-low-expansion titanium silicate glass with some aluminum-magnesium fluoride coating.

Unfortunately, project technicians found soon after deployment in 1990 that HST's best image had a pinpoint of light encircled by a hazy ring or "halo." They announced that a "spherical aberration" in HST's mirror—a defect only 1⁄25 the width of a human hair—prevented Hubble from focusing its light to a single point. Would this cripple the spacecraft? Many thought so, and NASA took a beating in the media for this "plumb dumb" error. Technicians, however, soon found a way with computer enhancement to work around the

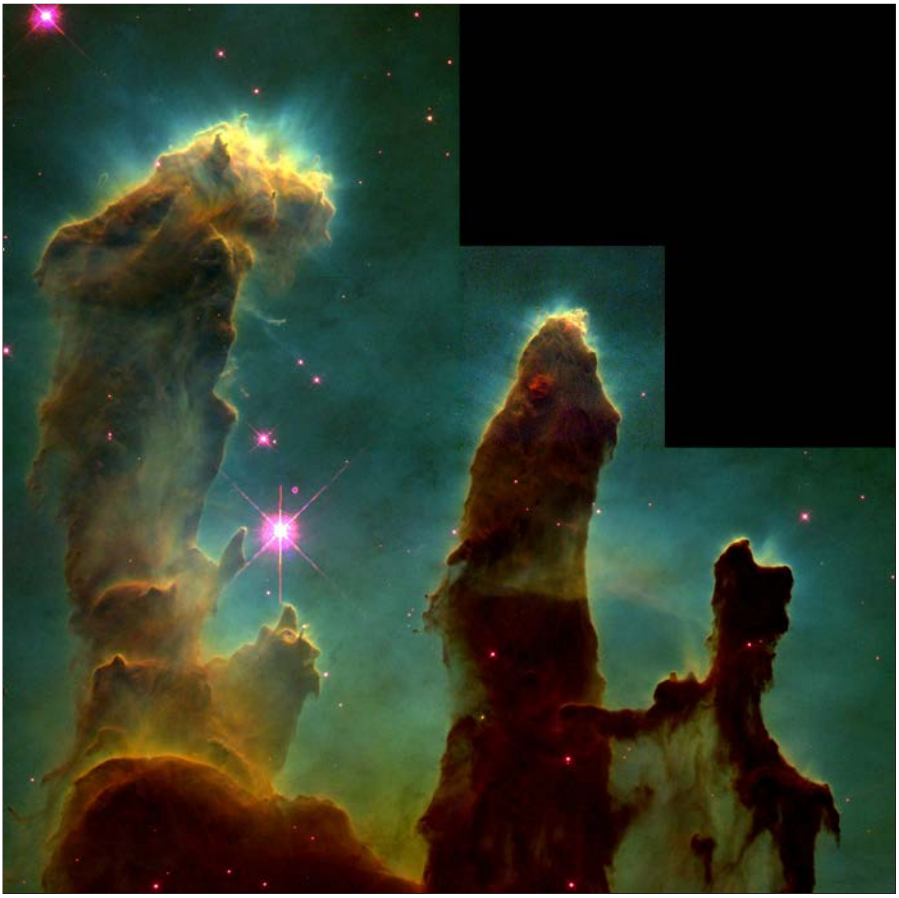

Figure 7-5. One of the most eerie and stunning images from the Hubble Space Telescope was released in 1995. The "Pillars of Creation" are part of the Eagle Nebula (also called M16) and depict the star formation "Nursery." (NASA, s95-19955)

abnormality, and engineers planned a Shuttle repair mission to fully correct it with additional instruments.

The first Hubble Servicing Mission took place in December 1993 when the Space Shuttle Endeavour undertook a repair mission to insert corrective optics into the telescope and to service other instruments. During a weeklong mission, Endeavour's astronauts conducted a record five spacewalks and successfully completed all programmed repairs to the spacecraft. The first reports from the Hubble spacecraft indicated that the images being returned were afterward more than an order of magnitude sharper than those transmitted before.

Thereafter, HST began returning impressive scientific data on a routine basis. For instance, as recently as 1980, astronomers had believed that an astronomical grouping known as R-136 was a single star, but the Hubble showed that it was made up of more than 60 of the youngest and heaviest stars ever viewed. The dense cluster, located within the Large Magellanic Cloud, was about 160,000 light-years from Earth, roughly 5.9 trillion miles away. HST has dominated astronomical discoveries through to the present.

In all, NASA has made five servicing missions to the Hubble Space Telescope using the Space Shuttle, with astronauts on each flight making a succession of spacewalks to replace components, repair failed systems, and enhance capabilities. The final Hubble servicing mission took place in 2009 to extend the instrument's service life well into the 2020s.

The Compton Gamma Ray Observatory

The second of NASA's Great Observatories was the Compton Gamma Ray Observatory (CGRO). Named for Arthur Compton, a Nobel Laureate for his studies of gamma-ray physics, CGRO was deployed on 5 April 1991 from the Space Shuttle Atlantis on mission STS-37. The initial phase of CGRO's science program consisted of a near-uniform survey of the celestial sky followed by specific concentrations in later phases. In the context of a service of almost 10 years, project scientists satisfied this mission objective. Among other findings, CGRO discovered in the Milky Way a possible antimatter source above the center and definitively showed that the majority of gamma-ray bursts must originate in distant galaxies, rather than the Milky Way, and therefore must be much more energetic than previously believed.

After 10 years of operation, CGRO's systems began to fail in a way that prohibited its continuation. Accordingly, the remaining fuel on the spacecraft placed it into a controlled reentry over the Pacific Ocean. It deorbited on 4 June 2000 and burned up in Earth's atmosphere.

The Chandra X-ray Observatory

The Chandra X-ray Observatory (CXO), named for the Indian-American Nobel Laureate astrophysicist Subrahmanyan Chandrasekhar, was the third of NASA's Great Observatories. CXO was deployed from the Space Shuttle Columbia on mission STS-93 on 23 July 1999 and subsequently boosted into an extremely high-Earth orbit. It focused on observing black holes, quasars, supernovae, dark matter, and high-temperature gases throughout the x-ray portion of the electromagnetic spectrum.

Chandra carried four sensitive instruments to image x rays from clouds of gas, some of them so vast that they are more than five light-years across. It has collected scientific data on the glowing remains of exploded stars and the dispersal of astronomical elements. Most importantly, since it provided the first imagery, Chandra observed the region around a supermassive black hole at the center of the Milky Way and found black holes throughout the universe. Chandra, furthermore, traced the separation of dark matter from normal matter in collisions of galaxies, greatly enhancing knowledge of dark matter and dark energy studies.

Chandra's mission is far from over. It continues to operate more than 20 years after its deployment in Earth orbit.

The Spitzer Space Telescope

Finally, the Spitzer Space Telescope, named for theoretical physicist Lyman Spitzer, Jr., was the last spacecraft assigned to NASA's Great Observatories program. It monitored celestial bodies in the infrared region of the electromagnetic spectrum, which is primarily heat radiation, something that cannot easily be done from Earth-based observatories because the planet's atmosphere blocks most interstellar infrared radiation. Launched by a Delta rocket on 25 August 2003, Spitzer detected infrared energy radiated by objects in space between wavelengths of 3 and 180 microns.

This telescope's location is in a trailing orbit of Earth around the Sun. This placement ensured that it was removed from Earth's heat and more able to detect exceptionally fine gradations of temperature. It has discovered brown dwarf stars, astronomical objects that do not possess enough mass to ignite and become full-fledged stars. Scientists observe that these brown dwarfs may provide insights into the dark matter thought to permeate the universe. Spitzer also imaged "ultra-luminous infrared galaxies" that operate almost solely in the infrared wavelength. Finally, it has probed distant galaxies at the farthest reaches of where human technology can reach.

After operating since 2003, on 15 May 2009, Spitzer's cryogenic coolers had reached their service life, but scientists were prepared and entered a new phase of operations without supercooling. They continued to use Spitzer to explore the infrared region—but without the sensitivity present before—until 30 January 2020, when the spacecraft was shut down.

Characterizing the Big Bang

The stunning success of NASA's Great Observatories program was extended to other astronomical instruments placed in space aimed at understanding the universe. Most specifically, the Cosmic Background Explorer (COBE), which flew during this same period as the Great Observatories, helped to characterize the origins of the universe as never before. Operating between 18 November 1989 and 23 December 1993, COBE searched for, and found, the microwave radiation left over from the Big Bang. It found two key pieces of evidence that supported the Big Bang theory of the origins of the universe: 1) the measurement of the temperature of the radiation left over from the Big Bang and 2) the relationship of that heat still present at the location of the origins event.

COBE's principal investigators, George Smoot III and John Mather, received the Nobel Prize in Physics in 2006 for their work on the project. According to the Nobel Prize committee, "the COBE-project can also be regarded as the starting point for cosmology as a precision science."[11] Mather, who coordinated the project and had primary responsibility for COBE's blackbody measurements of cosmic background radiation, was the first NASA scientist to win a Nobel Prize. Smoot had the responsibility of measuring the small variations in the temperature of the radiation.

Although the discoveries of the Wilkinson Microwave Anisotropy Probe (WMAP) have not yet led to a Nobel Prize for its scientists, it also proved enormously significant in characterizing the Big Bang and the early evolution of the universe. Between June 2001 and 2010, WMAP charted background radiation in minute detail across the universe. Launched into a halo orbit around the L2 libration point beyond Earth's orbit, WMAP found that cosmic background radiation was emitted about 13.77 billion years ago to within a half percent in the immediate aftermath of the Big Bang and has been stretched to the microwave part of the electromagnetic spectrum by the expansion of the universe. The WMAP data show a "clumping" of matter that occurred in the early history of the universe. It measured the cooling rate and time of the universe since the Big Bang with tiny fluctuations generated during expansion.

The James Webb Space Telescope

As these missions unfolded, NASA worked toward launching the James Webb Space Telescope (JWST), which would extend the investigations beyond these recent space-based observatories. Explicitly championed as a follow-on to the Hubble Space Telescope, JWST operates in a longer wavelength coverage with greatly improved sensitivity. NASA scientists envisioned it as an instrument that could peer back much closer to the origins of the universe and discover the formation of the first galaxies. Its chief scientist, Nobel Laureate John Mather, said of JWST: "Our resolution is better than Hubble and we will see early galaxies when they were young by using infrared. Also, Hubble can't see the very first galaxies but we will be able to."[12]

JWST pushed technology further than any earlier orbital observatory, something that contributed to several delays in deploying the instrument. Its primary mirror made of 18 separate segments of ultra-lightweight beryllium unfolds robotically and adjusts as needed once in space. It also has a tennis court–sized sunshield that decreases heat from the Sun to keep the telescope operating at optimum efficiency. Although it faced both launch delays and technological challenges throughout the 2010s, NASA launched JWST on an Arianespace Ariane 5 from French Guiana on 25 December 2021, and its mission is beginning to unfold.

Extrasolar Planets

Since the 1990s, the detection of planets around the other stars has transformed understanding of the cosmos. The first indirect detection of a planet orbiting Gamma Cephei in 1988 set the community astir even as it went unconfirmed for several years. In 1992 a second planet was announced orbiting a pulsar. This was surprising, but in 1995 astronomers found a planet orbiting a star similar to the Sun. The discoveries exploded thereafter, mostly coming from ground-based observers. Advances in detection instruments, as well as computing power and data processing, allowed the cataloging of ridiculously small movements detected through gravity lensing. Virtually all of these were massive gas giants orbiting other stars, but in the first two decades of the 21st century further technological advances allowed the detection of very small bodies and even the imaging of some exoplanets.

NASA developed the Kepler mission, launched in 2009, to perceive the presence of planets, especially terrestrial ones that might be Earth-like. The first exoplanet confirmed by Kepler to have an average orbital distance within its star's habitable zone was Kepler-22b, exciting the planet hunter community that it could potentially be Earth-like. Located about 600 light-years away from Earth in the Cygnus constellation, Kepler-22b's radius is roughly 2.4 times the radius of Earth, although most of its other features are unknown. Speculation that it might be a watery planet abounds, leading scientist Natalie Batalha to comment in December 2011 that "it's not beyond the realm of possibility that life could exist in such an ocean."

Cataloging what it had found through March 2020, scientists working on the Kepler project have discovered 2,682 exoplanets, and there are more than 2,900 candidate planets awaiting confirmation—history suggests most of those are the real deal. From all sources as of 1 February 2020, there are 4,173 confirmed exoplanets in 3,096 systems, with 678 systems having more than one planet. Additional planets are being placed in the catalog almost daily. Whether any of these are truly Earth-like and might harbor life are some of the core questions yet unanswered. Exoplanet hunters are hard on the trail of atmospheres, temperatures, and sizes that are comparable to Earth's. Future instruments may yet confirm the existence of exo-Earths.

Studying Earth as a Planetary System

While all of this was taking place NASA also undertook efforts to use space-based satellites to learn about Earth as a planet. In 1962 NASA sponsored its first conference discussing the possibilities of space-based Earth observations. It also pursued a large-scale effort to lay the groundwork in Earth system science at its Goddard Space Flight Center's Division of Aeronomy and Meteorology under William Stroud. Without question, data from NASA technology, satellites, institutes, scientists, and organizational initiatives were essential in creating the global picture of Earth as a system that emerged later.

NASA scientists quickly pursued weather satellites as a unique aspect of its missions. As a justification they used the National Aeronautics and Space Act of 1958, which mandated NASA to work with other organizations, in this case the Weather Bureau, to develop technology programs that supported its mission within the "applications" portion of NASA's mission. These efforts fostered the Agency's leadership of a broad-based Earth system science effort by the 1980s. Over time, a succession of missions has enabled greater understanding of the evolution of Earth as a biosphere.

As a starting point, NASA launched Television InfraRed Observational Satellite (TIROS 1) on 1 April 1960, and it proved successful from the outset, despite technical problems and difficulties in working across several federal agencies. "Two television cameras looking down from an altitude of about 450 miles made initial pictures of the earth's cloud patterns during the satellite's second orbital trip," reported the *New York Times* just after the launch.[13] Unveiled by NASA, as the federal agency responsible for the TIROS program, the representatives of the Weather Bureau and the Eisenhower administration gushed about the prospects for future observation of weather patterns and better forecasting that an operational weather satellite system would provide. The satellite provided valuable images of weather fronts, storms, and other atmospheric occurrences. It led directly to a long series of weather satellites that quickly became standard weather forecasting tools in the United States and throughout the world. TIROS helped meteorologists forecast patterns and study weather and climate.

With the success of TIROS, NASA and the Weather Bureau embarked on a succession of experimental weather satellites, some named TIROS but also a second-generation satellite called Nimbus. More complex than TIROS, Nimbus carried advanced TV cloud-mapping cameras and an infrared radiometer that allowed pictures at night for the first time. Seven Nimbus satellites were placed in orbit between 1964 and 1978, creating the capability to observe the planet 24 hours per day. Turning weather satellites from an experimental program to an operational system proved daunting. To accomplish this, NASA and Weather Bureau scientists organized an interagency Panel on Operational Meteorological Satellites in October 1960. Developers, scientists, other users, and various federal agencies aired disagreements over the future of the program in this setting; the meetings were often contentious. The Weather Bureau sought complete authority over the planned operational system, including launching, data retrieval, and final decisions on the design of new operational satellites.

The ESSA (Environmental Science Services Administration) 1 through 9 satellites provided some upgrade to what had gone before. Additionally, meteorological satellites that were part of NASA's Applications Technology Satellite (ATS) project to orbit experimental geosynchronous satellites proved valuable. In December 1966 and November 1967, ATS 1 and 3 explored the possibility of observing weather with line scan imagers; the resulting continuous coverage proved valuable for short-lived cloud patterns correlated to tornadoes. Continuous coverage from geosynchronous orbit made it possible to observe the motion of clouds and deduce wind speed at the level of the clouds. Three other satellites launched in the 1960s, ATS 2, 4, and 5, also carried meteorological experiments.

While the study of weather patterns was truly significant in laying the groundwork for the emergence of Earth system science, planetary scientists early on realized that their efforts in planetary climatology, geology, geodesy, biology, chemistry, and magnetospherics for Venus and Mars also had applications for Earth. A National Research Council (NRC) study observed in 1961:

"the development of satellites and space probes without question is adding a new dimension to these capabilities. It seems likely that in the years ahead we will learn more about the Earth by leaving it than by remaining on it."[14]

It was clear, as stated in a 1962 NRC report, that the entrée of scientists into Earth observation came because of the desire to focus on Venus and Mars. "Much of our knowledge of the planets has been and will continue to be based on lessons learned from studying our own planet." The report concluded, "With this in mind, it is clear that no opportunity should be lost to test out planetary probe experiments from rockets and Earth satellites. In addition to serving as 'field tests' for new equipment and techniques, these tests can be valuable scientific experiments in their own right, and in all likelihood will give vital information about our own planet."[15]

Landsat

In the latter 1960s NASA began working on the Landsat Earth monitoring program as a realization of what might be learned about Earth from space. Although not initially viewed as a science program, but rather a technology demonstrator, Landsat 1's launch on 23 July 1972 changed the way in which many people viewed the planet. It provided data on vegetation, insect infestations, crop growth, and associated land use. Overall, there have been seven Landsat spacecraft launched; the effort has enhanced worldwide crop forecasting. Moreover, Landsat imagery has been used to devise a strategy for deploying equipment to contain oil spills, to aid navigation, to monitor pollution, to assist in water management, to site new power plants and pipelines, and to aid in agricultural development.

By the 1970s such programs as Landsat and LACIE (Large Area Crop Inventory Experiment), an Earth observation project using Landsat satellites to gather data, were becoming indispensable. So too was a relatively small project to study stratospheric ozone depletion within the NASA science organization. In part, this resulted from the Space Shuttle's own potential to deplete ozone, but this initiative became politically salient very rapidly as the first of the American "ozone wars" broke out around chlorofluorocarbons. James C. Fletcher, outgoing NASA Administrator in 1977, remarked that these efforts represented the "'wave of the future' as far as NASA's public image is concerned. It is the most popular program (other than aeronautics) in the Congress and as you begin to visit with community leaders, you will understand it is clearly the most popular program with them as well."[16] These efforts in the 1970s rested firmly on the base established in earlier eras. By the end of that decade NASA had committed more funding to Earth science than any other federal organization and its organization structure had evolved to oversee expansive scientific investigations about Earth across a broad spectrum of disciplines and technologies.

When Mount St. Helens erupted on 18 May 1980, for example, satellites tracked the tons of volcanic ash that spread eastwardly, allowing meteorologists both to warn of danger and to study the effects of the explosion on the world's climate. More spectacular, and ultimately more disconcerting, Nimbus 7, in orbit since 1978, revealed that ozone levels over the Antarctic had been dropping for years and had reached record lows by October 1991. These data, combined with that from other sources, led to the 1992 decision to enact U.S. legislation banning chemicals that depleted the ozone layer.

In the 1980s, NASA and the National Oceanic and Atmospheric Administration (NOAA) also began developing the Geostationary Operational Environmental Satellite (GOES) system, which viewed the entire Earth every 30 minutes, day and night, and placed seven GOES spacecraft into orbit. As the 1990s began, a series of five new satellites, designated GOES-I through -M, was under development by NASA and NOAA for use beyond the year 2000.

Mission to Planet Earth

In the aftermath of the Challenger accident in January 1986, NASA commissioned astronaut Sally Ride to undertake a study of NASA programs and recommend an approach for future missions. *NASA Leadership and America's Future in Space: A Report to the Administrator* appeared in 1987. The so-called "Ride Report" proposed four main initiatives for study and evaluation:

1. Mission to Planet Earth
2. Exploration of the Solar System
3. Outpost on the Moon
4. Humans to Mars

The "Mission to Planet Earth" initiative called for the expansion of Earth science and the application of new technologies to understand Earth as a planet and the changes that may be taking place on it.

While there had to be rescoping of the program over time, this report served as the catalyst for an investment of more than $7 billion to build and operate a series of orbital spacecraft and to analyze data from them for environmental purposes. The program's Earth Observing System (EOS) satellites consisted of a range of remote sensing satellites that collected data in a variety of ranges on air, land, and sea bodies on the planet.

In 1991 NASA formally established Mission to Planet Earth (MTPE) as a comprehensive program for studying Earth from space. It emphasized the integration of data from various Earth observing instruments and programs to gain a greater understanding of Earth's natural processes on a global scale. The perspective provided new levels of precision to the evaluation of pressure fronts and air masses that are so critical in weather forecasting. Likewise, meteorological research beyond weather forecasting took on new life as climatological research contributed significant insights to our understanding of Earth.

By 2000, Earth system science had matured, and throughout the 21st century a variety of Earth observing spacecraft have enabled scientists to obtain sophisticated data about this planet's physical characteristics. Among others, these spacecraft included the Tropical Rainfall Measuring Mission (TRMM), the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission, the QuikScat and TOPEX/Poseidon ocean studies missions, and the Active Cavity Radiometer Irradiance Monitor Satellite (ACRIMSAT) and Upper Atmosphere Research Satellite (UARS) missions. Instruments from these satellites have measured atmospheric chemistry, biomass burning, and land-surface changes ranging from Greenland to the tropical Pacific Ocean. Together, these spacecraft have transformed our understanding of Earth. Cooperatively, they have shown changes in the atmosphere, land, and oceans, as well as their interactions with solar radiation and with one another.

The Global Warming Debate

By the early part of the 1990s, the emerging discipline of Earth system science had become part of the lexicon and had already made inroads into the public consciousness. It took on added significance as debates over global climate change, sometimes referred to as "global warming," became more politicized as the decade progressed. Some opponents of regulation were irate about the use of scientific studies by government officials as justification for restrictive protocols that circumscribed their actions. Those opposed to change focused on questioning the science on which the government has based its actions.

This effort found expression in one of the most difficult situations NASA has ever faced. In 2005 some NASA officials attempted to silence scientific findings about global climate change. This began as a tragicomic effort of some political appointees to control scientists associated with the federal government by keeping them from taking positions on hot-button issues, especially global warming. NASA scientist James R. Hansen was a central participant in this controversy. He had been involved in research about global warming since the 1970s, and his organization, NASA's Goddard Institute for Space Studies in

Manhattan, had a long tradition of tracking the rising annual global temperatures over the decades since the Space Age began.

Hansen had been arguing for decades that evidence compels action to combat global warming by reducing the level of CO_2. For example, in June 1988 he told a U.S. Senate committee of the potential hazard of climatic changes. One sentence caught the public's attention: "It's time to stop waffling…and say that the greenhouse effect is here and is affecting our climate now."[17] Such strident statements did not endear Hansen to political leaders who faced opposition from business interests. He did not face an expressly partisan backlash at first, but there was always a backlash. Some in both political parties believed action needed to be taken and others on both sides also believed no action was required. That has changed over the years, and the response to global warming has taken on the color of the two parties and their priorities.

By 2005, however, political appointees in the NASA Office of Public Affairs were working to keep Hansen's research on global warming buried. This took several forms: questioning the science or emphasizing that consensus on the meaning of the scientific data did not exist. In a few instances, press releases cast doubt on what Hansen and other climate scientists insisted was the undeniable fact of global warming.

There were others also involved in censoring the presentation of scientific data about global climate change. The person that was seemingly most involved was a junior public affairs officer at NASA Headquarters who exerted more pressure on the system than his position should have allowed. He modified press releases, tried to control who spoke with scientists, and repeatedly put partisan loyalties above seemingly inviolate ethical considerations in the pursuit of science. It was this scientific censorship that ignited the public debate that quickly led to the reversal of these actions.

Journalist Andrew Revkin's bombshell front-page *New York Times* article on 29 January 2006 opened this issue to public scrutiny. It led to official NASA policy statements affirming scientific independence and permitting scientists the freedom to publish their results without censorship. But this came only after the actions of several civil servants both inside NASA and out who worked, often quietly, to make sure scientists could report their findings. The chief among them was James Hansen, but career public affairs officers sought to assure scientific independence. Within days, NASA affirmed its commitment to clear communication of scientific findings unfettered by political considerations. NASA Administrator Michael Griffin stated: "The job of the Office of Public Affairs, at every level in NASA, is to convey the work done at NASA to our stakeholders in an intelligible way. It is not the job of public affairs officers to alter, filter or adjust engineering or scientific material produced by NASA's technical staff."[18]

At one level this was a sad episode in the history of NASA, a subversion of the continuing quest for scientific knowledge and understanding. While NASA officials have made mistakes over the Agency's history, there is no instance in NASA's past in which there was a cabal in place systematically seeking to change scientific findings to fit some preordained position. But at another level, it was a genuine success story. It shows how NASA's committed workforce could rise to a challenge and succeed in ensuring the integrity of the scientific process, the knowledge gained through empirical research, and the Agency's commitment to understanding the realities of the cosmos. It was something of a bellwether for NASA's role as an honest broker of scientific knowledge. Whether it be about Earth system science, planetary exploration, or the universe beyond, the objective has always been the same, the search for truth.

Legacies

The successes and challenges that NASA has wrestled with in its pursuit of scientific truth have sometimes been invigorating, sometimes disconcerting, and sometimes surprising. Over the more than 60 years of the Space Age, NASA's scientists, engineers, technicians, managers, and executives in the space science arena have sent probes to visit every planet in the solar system, some of them many times, and pushed back the frontiers of knowledge about these bodies. They have searched for life beyond Earth—without finding it as yet—and sought to understand humanity's place in the cosmos. We may conclude about this endeavor, as legendary news reporter Walter Cronkite gushed about the whole of NASA in 2000: "Yes, indeed, we are the lucky generation." In this era we "first broke our earthly bonds and ventured into space. From our descendants' perches on other planets or distant space cities, they will look back at our achievement with wonder at our courage and audacity and with appreciation at our accomplishments, which assured the future in which they live."[19] In every case, the best response remains that seen in Times Square during the landing of Curiosity in 2012: "Sci-ence, Sci-ence, Sci-ence!"

CHAPTER 8

Achieving Reusable Space Access

In the sweltering heat of summer 1965, NASA's High-Speed Flight Facility, located in the Mojave Desert of California, buzzed with activity. NASA engineers pursued several types of lifting-body spaceplanes that offered promise for moving beyond space capsules for astronauts reaching into orbit. No astronaut enjoyed splashing down into the ocean aboard a space capsule dangling from parachutes. No astronaut wanted to be rescued at sea. As high-performance test pilots, they all wanted to land a spacecraft as they did their jets, on a runway. And the astronauts were not alone. NASA's engineering community wanted the same thing; so did their organizational leadership. They had abandoned the dream of spaceplanes in the 1950s and adopted capsules only as an expediency during the space race.

Expressing these desires, Weneth D. Painter at NASA's Mojave facility captured the mood of the space agency for a post-Apollo space vehicle. He drew a cartoon in 1965 showing in one panel a Gemini spacecraft bobbing in the ocean as its crew, turning green and fighting off sharks, awaited rescue at sea. In another panel was a spaceplane landing on a runway, the crew deplaning and walking on a red carpet to waiting ground transportation. The caption read: "Don't be rescued from outer space, fly back in style." It captured the key difference between space capsule splashdowns at sea and spaceplane landings on a runway. It expressed well the elegance of a spaceplane, an approach that was incompletely realized with the Space Shuttle but still something that has remained an objective of human spaceflight ever since those first flights of the Shuttle in the 1980s. Both approaches to spaceflight work; one is viewed as more elegant than the other.

The Space Shuttle was an attempt to create an elegant solution to the challenge of spaceflight, but not a fully successful one. Starting as a formal program in 1972, the first Shuttle to reach space launched on 12 April 1981, 20 years

Figure 8-1. Weneth Painter penned this cartoon in 1965 to show the desire for a spaceplane. (NASA EC66-1321)

to the day after Yuri Gagarin's first flight. In all, 135 Shuttle missions took place between 1981 and 2011. The space vehicle became a symbol of American technological prowess, recognized worldwide as such in both its triumph and its tragedy. During its lifetime, the Space Shuttle program used nearly a third of the Agency's budget. It registered enormous triumphs and horrendous tragedies, especially the two accidents that cost the lives of 14 astronauts.

The Space Shuttle Decision

The Space Shuttle had been conceived early in NASA's history as an integral part of a much larger program to provide logistics support to a space station, which would then be used as the jumping off point for missions to the Moon and Mars. The goal of the new vehicle was simple, to provide “routine access to space” at an economical cost. Studies NASA conducted in the mid-1960s found that reusable space technology was within reasonable grasp, more evolutionary than revolutionary, and that a hefty investment of research and development funds could yield a substantial reduction in operations costs. Flying 20 or more times a year, NASA leaders believed, such a system would be an economical alternative to the use of large “throwaway” launchers like the Saturn.

The goal of efficient operations in a heavy-lift booster—especially with the decision for budgetary reasons to terminate the Saturn V booster production line in mid-1968 after the completion of 15 launch vehicles—prompted NASA’s commitment to the Shuttle as a continuation vehicle for human spaceflight. Once it was under way, NASA leaders believed, they could also move forward with a space station, which the Shuttle could both place in orbit and support logistically. In addition, and this was pure serendipity from the NASA perspective, because of the Shuttle’s size and versatility, a portion of its payload bay could be used to haul scientific and applications satellites of all types into orbit for all users. The Shuttle was to be, essentially, the realization of a one-size-fits-all launcher, in this instance the vehicle providing all orbital services required by users. This type of standardization has long been an important part of American mass production, the Model-T automobile and the F-4 fighter aircraft being examples of how it was supposed to work.

By the latter part of the 1960s, even as Apollo was under way, the reusable Space Shuttle had become an integral part of NASA’s much larger objective of building a space station and launching a human mission to Mars. George E. Mueller, NASA’s Associate Administrator for Manned Space Flight, formally unveiled preliminary studies and designs at a raucous August 1968 annual meeting of the British Interplanetary Society and set the aerospace world abuzz with this exciting new concept intended to make reaching space an easy, cheap, and reliable actuality. As the Apollo Moon landings reached fruition in 1969, the new presidential administration of Richard M. Nixon commissioned on 13 February 1969 a Space Task Group (STG) under the leadership of Vice President Spiro T. Agnew to determine next steps in space. Working with NASA, the aerospace industry, the U.S. military, and space advocates, this Group’s report incorporated NASA’s desires for a reusable Space Shuttle into its expansive vision of the future that also included a space station, a Moon base, and a human expedition to Mars. The President did not agree, forcing the space agency to back away from its overall goals and accept something less. That “something less” became the Space Shuttle.

After two years of inaction, in the summer of 1971 Caspar Weinberger, Deputy Director of the Office of Management and Budget (OMB), pressed

NASA's case for the Shuttle in the White House. Weinberger wrote a 12 August 1971 memorandum to Nixon, arguing that "there is real merit to the future of NASA, and to its proposed programs." The memo suggested that further cuts to NASA's budget "would be confirming in some respects, a belief that I fear is gaining credence at home and abroad: That our best years are behind us, that we are turning inward, reducing our defense commitments, and voluntarily starting to give up our super-power status, and our desire to maintain world superiority." Weinberger added that "America should be able to afford something besides increased welfare, programs to repair our cities, or Appalachian relief and the like." With the larger plans of NASA unviable in the Nixon administration, Weinberger made the case for approval of the Space Shuttle. In a handwritten scrawl on Weinberger's memo, Nixon wrote, "I agree with Cap."[1]

Nixon's decision to go ahead with the Shuttle project prompted a meeting on 5 January 1972 with NASA Administrator James C. Fletcher at the President's retreat in San Clemente, California, where NASA received formal approval to "proceed at once with the development of an entirely new type of space transportation system designed to help transform the space frontier of the 1970s into familiar territory, easily accessible for human endeavor in the 1980s and '90s."[2] The Shuttle became the largest, most expensive, and most visible project undertaken by NASA after Apollo; it continued to be a central component in the U.S. space program until the program's end in 2011.

Although the completed Space Shuttle is strikingly different from the one that spaceflight advocates envisioned initially, its core task remained the same. Both then and even after the design was altered, NASA intended to lower the cost of spaceflight as a precursor to an aggressive space exploration effort. NASA officials viewed both the Shuttle and a proposed space station as the necessary infrastructure to support efforts to get off this planet and reach Earth orbit. They recognized, appropriately so, that the most difficult part of spaceflight was leaving the surface of this planet, climbing out of the gravity well that we live in, and reaching an orbital velocity. Doing so easily, flexibly, economically, and safely became the key element in a long-term spacefaring vision that found expression in the Space Shuttle. Indeed, from virtually the beginning of the 20th century, those interested in the human exploration of space have viewed as central to that endeavor vehicles that could travel easily to and from Earth orbit. The quest for the Space Shuttle exemplified those ideals.

NASA Deputy Administrator George M. Low clearly declared the Agency's intentions on 27 January 1970: "I think there is really only one objective for the Space Shuttle program, and that is 'to provide a low-cost, economical space transportation system.' To meet this objective, one has to concentrate both on low development costs and on low operational costs."[3] From the outset, therefore, the economics of the Shuttle outweighed any other aspects of the program. This was a striking difference from previous NASA human spaceflight efforts.

From the Program Management Concept to Lead Center

NASA had instituted a program management concept to accomplish the Apollo Moon landings, and it worked exceptionally well. It was, however, enormously expensive. NASA officials realized at the conclusion of the Apollo program that they would never again have the resources available for the Moon landings and they had to find another means of accomplishing their projects without such a broad effort. Perhaps most important, the experience of Apollo suggested that this approach was fragile and could easily become flawed if its managers failed in strictly overseeing all aspects of the project. To do so, however, required enormous funding and personnel resources. In the face of conflicting organizational demands and restrictive budgets, the practices so successful in Apollo faced a high probability of failure.

In a series of meetings during September and October 1969, NASA leaders reconsidered their project management concept and took a decision to implement a "Lead Center" approach to building the Space Shuttle. No longer would there be an overarching project management organization at NASA Headquarters. Instead, they proposed a bi-center management structure with the Manned Spacecraft Center (renamed the Johnson Space Center in 1973) taking charge of managing the design, development, and building of the Shuttle orbiter and the Marshall Space Flight Center overseeing the development of the launch system on which the orbiter would ride into space. These two Centers were "lead" in their respective areas without the overweening NASA Headquarters oversight that had been present in Apollo.

This Lead Center concept, therefore, required much more responsibility and accountability at the Center level than ever before. It allowed the development of autonomous Center project offices; but for all the efficiencies that might have been realized otherwise, it also led to significant inter-center squabbling over resources and lines of authority.

Modifications to the "Lead Center" approach evolved thereafter. Despite challenges, NASA managers overseeing Space Shuttle development accomplished their tasks. While there was no question that the Space Shuttle was a creature of compromise that did not enjoy a universally positive reputation, its faults were not the result of the lead center management approach. In terms of only one measure, the cost from program approval through first flight was $5.974 billion (when adjusted for inflation to 1972 dollars), a 17 percent overrun above a $5.15 billion budget originally approved by Nixon's Office of Management and Budget. For the development effort, NASA did not do too badly in estimating costs in an era of rampant inflation during the 1970s.

Contrarily, the Apollo program, which enjoys a reputation as a highly successful, well-managed program using the program management concept, spent $21.4 billion in non-adjusted funds from project start to the first Moon landing. Other factors beyond the management of the research and development (R&D) effort for the Shuttle account for its checkered reputation, and most of them were the result of operational costs far in excess of what was envisioned by NASA at the R&D stage.

The lead center concept used during the Space Shuttle Program has been tried in subsequent NASA projects with mixed results. Over time, the space agency has moved toward greater center responsibility and authority for projects, and then away from this approach, depending on circumstances.

Building the Space Shuttle

The Space Shuttle that emerged in the early 1970s consisted of three primary elements: a delta-winged orbiter with a large crew compartment, a 15- by 60-foot cargo bay, and three main engines; two solid rocket boosters (SRB) attached to an external fuel tank housing the liquid hydrogen and oxidizer burned in the main engines. The orbiter and the two solid rocket boosters were reusable. The Shuttle was designed to transport approximately 45,000 tons of cargo into near-Earth orbit, 200 to 300 miles above Earth. It could also accommodate a flight crew of up to 10 persons, although a crew of 7 would be more common, for a basic space mission of seven days. During a return to Earth, the orbiter was designed so that it had a cross-range maneuvering capability of 1,265 miles to meet a military requirement for liftoff and landing at the same location after only one orbit.

NASA began developing the Shuttle on 31 March 1972, when it selected Rockwell International to design and develop the main engines. Contracts followed to Martin Marietta for the external fuel tank on 16 August 1973 and to Morton Thiokol for the solid rocket boosters in June 1974. On 26 July 1972, NASA selected Rockwell to design and build a test orbiter and four operational vehicles.

There were several challenges to be met in building this partially reusable system. One involved the reusability of the Space Shuttle main engines, the first such rocket motor ever developed. It was to operate for 55 missions, or 27,000 seconds, including the ability to operate six times at an "emergency power level" of 109 percent. The ability to operate above 100 percent was intended as a safety

Figure 8-2. The best view of a Space Shuttle launch is just after liftoff, as it clears the tower. On 3 October 1988, STS-26 marked the return to flight for the Space Shuttle after the tragic Challenger accident of 27 January 1986. (NASA, EL-1997-00011)

feature in case it was ever needed, but every time it would stress the technology and had to be tracked carefully, hence the six times limitation. This was a very tall order, and the R&D required to build this engine cost more, and took more time, than envisioned. Likewise, the orbiter's thermal protection system (TPS), which also had to be reusable, proved difficult. NASA had to develop a special heat resistant ceramic tile to be placed on the underside and nose of the orbiter to withstand the reentry heat, as well as thermal blankets and other protective components of the TPS. Because of these issues, as well as political and management questions, the Shuttle development program bogged down seriously in the mid-1970s, prompting its redefinition and refinancing and a delay of its first operational flight from 1979 to 1981.

The first orbiter, Enterprise (OV-101)—named for the spacecraft made famous in the *Star Trek* television series after a promotional campaign by "trekkers" such as had never been seen before in space program history—rolled out of the Rockwell contractor plant on 17 September 1976. In January 1977, Enterprise moved overland to NASA's Dryden Flight Research Facility in southern California, towed at a snail's pace on California State Highway 14 to the NASA installation with an army of wing walkers ensuring that it moved safely, and made its first flight atop its Boeing 747 test platform on 18 February. Those "captive" tests continued through most of the summer of 1977, but on 12 August, the first free flight took place. Some difficulties did materialize in this test program.

On the fifth and last free flight on 26 October 1977, Enterprise encountered control problems at touchdown. While trying to slow the spacecraft for landing the pilot experienced a left roll, corrected for it, and touched down too hard. The Shuttle bounced once and eventually settled down to a longer landing than expected. This "pilot induced oscillation," as it was called, was occasioned by the pilot taking over from an automated system too late and not allowing himself sufficient time to get the "feel" of the craft. It was, fortunately, self-correcting when the pilot relaxed the controls, and the positive result led to a decision to take Enterprise on to the Marshall Space Flight Center in Huntsville, Alabama, for a series of ground vibration tests. Several other test elements—engines and associated systems—were completed during the latter part of the 1970s, each directing the program toward an orbital flight in 1981.

The Changing Astronaut Corps

The Space Shuttle Program enabled NASA to recruit a much wider number and type of astronauts, those with pilot skills as well as scientific and technical specialties. Throughout the first 20 years of NASA's history, it had taken well-deserved criticism for its lack of diversity in an increasingly diverse America. Nothing demonstrated this more than the entirely white male astronaut corps of the 1960s. The Space Shuttle Program ended the domination of astronauts with the "Right Stuff," a characterization that symbolized these individuals as testosterone-imbued daredevils. The new astronauts were still heroes in the best sense of the term, but there were just as many scientists and scholars as fliers.

For the first time in NASA's history, the most important aspects of performing the astronaut function did not take place in the cockpit, but rather in the science laboratory. Those riding into space in the orbiter's mid-deck had at least as significant a job as those piloting the vehicle.

Accordingly, among other notable developments, the Shuttle enabled an expansion of the astronaut complement from those who were first and foremost pilots, expanding the pool of potential candidates to a much broader set of Americans, including women and minorities. The 1978 class of astronauts, the first one recruited for the Space Shuttle Program, included six women. In June 1983, Sally K. Ride, a NASA scientist-astronaut selected in that class, became the first American woman to fly in space aboard STS-7. Kathy D. Sullivan, another member of that class, became the first American woman to undertake a spacewalk during STS-41G on 11 October 1984.

Also, that 1978 class of astronauts included three African Americans, and in August 1983 Guion S. Bluford became the first African American astronaut to fly on STS-8. Also selected in the same astronaut class, Ronald E. McNair flew on STS-41D and lost his life on STS-51L, when Challenger broke up on launch on 28 January 1986. The third, Frederick D. Gregory, flew three Space Shuttle missions and went on to become NASA Deputy Administrator between 2002 and 2005. Ellison Onizuka, furthermore, was the first Asian American to enter the NASA astronaut corps, flying on the STS-51C and STS-51L missions, also losing his life on Challenger in 1986.

During the early Shuttle era, NASA inaugurated both a payload specialist program to fly individuals associated with specific experiments as well as a "Space Flight Participant Program" aimed at allowing nonscientists or nonengineers to experience orbital flight. The first person was a teacher, Christa McAuliffe, who died in the Challenger accident in January 1986, but a journalist and perhaps a poet were also possibilities for future missions. Notably, educator Barbara Morgan flew toward the end of the Shuttle program.

In addition, astronauts from many other nations flew aboard the Shuttle, including astronauts from Russia, Israel, Saudi Arabia, Canada, France, Germany, Italy, Japan, and Switzerland. This democratization of human spaceflight was a major attribute of the Shuttle era and the result of its flexibility as a space vehicle. The first European Space Agency astronaut to fly in 1983, Ulf Merbold, commented afterward, "For the first time in my life I saw the horizon as a curved line. It was accentuated by a thin seam of dark blue light—our atmosphere. Obviously, this was not the ocean of air I had been told it was so many times in my life. I was terrified by its fragile appearance."[4] Like many others before, this unique vantage point prompted Merbold to realize the need to preserve Earth for future generations.

This era also saw flights by politicians, although it opened NASA to well-placed criticism. Senator Jake Garn (R-Utah) and Representative Bill Nelson (D-Florida) both left Congress long enough to fly on the Shuttle in late 1985 and early 1986, respectively. At least the two major parties were represented in this group. Opponents accused NASA of pandering to Congress and other constituencies for support by offering such perquisites to a carefully selected few. *Doonesbury* cartoonist Garry Trudeau skewered Garn with a succession of appearances. In one, he showed Garn rehearsing memorable statements that he might make from orbit. He rejected all of them until he decided upon, "One giant leap towards approving the 1986 NASA budget."[5]

Despite such skewering, the ploy worked. Nelson became a longstanding proponent for NASA funding in Congress and offered this assessment of the space program: "If America ever abandoned her space ventures, then we would die as a nation, becoming second-rate in our own eyes, as well as in the eyes of the world…. Our prime reason for commitment can be summed up as follows…space is our next frontier."[6] With the establishment of the Joe Biden administration in January 2021, Nelson went on to be appointed as the NASA Administrator. Of course, the most famous instance of a politician flying was the return to flight of John Glenn in 1998 aboard STS-95. While this was clearly a favor for a valued Democratic leader in the U.S. Senate during the presidency of Bill Clinton, it was also at some level recognition of Glenn's life of sacrifice and courage as a Marine combat pilot and Mercury astronaut. Walter Cronkite, who came out of retirement to cover this mission, perhaps summed it up best when he said, "as far as I'm concerned, John Glenn is a hero and he can do pretty much whatever he wants."[7] It is obvious that the flexibility of the Space Shuttle as a human space vehicle could serve both a positive and a negative purpose depending on the politics of the situation.

NASA and the Continuing Challenge of Workplace Diversity

Although it is a stellar science and engineering organization, NASA has always lagged behind as American society has changed. The latter third of the 20th century saw a remarkable transformation in the nation as social groups advocated for and gained ever greater parity in the workplace and elsewhere. NASA trailed most of the nation in putting in place equal rights for African Americans, women, other minorities, and other protected groups. The long, slow, halting, and mixed advance of equality at NASA discussed earlier concerning African Americans may also be seen in initiatives for greater gender equality in a heavily white male engineering organization. Some strides were made in the astronaut corps beginning in 1978, of course, but what about other professionals at NASA?

Figure 8-3. Jerrie Cobb, one of the women who underwent the same physical tests as the Mercury astronauts in the early 1960s, prepares to operate the Multi-Axis Space Test Inertia Facility (MASTIF) inside the Altitude Wind Tunnel at NASA's then–Lewis Research Center. (NASA, GRC-1960-C-53088)

There were always some women in highly skilled professional positions at NASA, but through much of the history they were the exception that proved the rule. In July 1962, George M. Low testified for NASA to Congress at a hearing concerning the women who had undergone the same tests as the Mercury astronauts and advocated for their entrance into the astronaut corps. NASA shut that effort down cold, but Low went further to comment on the larger place of women in science and engineering at NASA. He proudly stated that "we now have in NASA a total of 146 women who are classified as professional aerospace technologists. These are engineers." He added that another 77 women at NASA were mathematicians. What he did not say was that these 223 women were part of a civil service workforce of 33,200 scientists and engineers at NASA in 1962, representing only .007 percent of the total.

Low failed to see any problem with this situation. He also claimed: "I don't believe, Mr. Chairman, that there is any discrimination against women in aerospace engineering." The dearth of women in the field, he commented, was because of a "lack of interest on the part of the average woman."

The women who did pursue a career at NASA were drawn to the Agency because of the really significant work under way to push back the frontier of flight. They reflected the same enthusiasm for spaceflight as their male counterparts and expressed pride in contributing to such an important and exciting objective.

A case in point was JoAnn Morgan, who retired in 2003 from the Kennedy Space Center (KSC), Florida, after a career that spanned more than four decades. As an undergraduate engineering student at the University of Florida, Gainesville, in 1958 she began interning at KSC and went to work there full time when she finished her degree. Her first job was in the "Blockhouse," a building that did not have women's restrooms. With tears in her eyes, she talked about how she had to find a guard to accompany her to the restroom, who would ensure no men were inside and then stand guard while she used the facilities. "Sometimes during tests, the guard was just great," she recalled. "He'd come over and say, 'You need a little break? I'll police the men's room'."[8] This was not a short-term inconvenience; she worked there for 15 years. This may not have been discrimination in a way that George Low would recognize it, but it was nonetheless discrimination. Morgan also recalled other, more overt discrimination. Sometimes there were obscene phone calls and "cat-calls," sometimes men received promotions she believed she deserved more. She persevered, even excelled, leading the Center's Computer Services Division, and then moving on to other KSC positions, in 2002 becoming acting KSC Center Director for a time.

JoAnn Morgan's experience was similar to that of many other women who worked in NASA's engineering and science organizations. Some expressed bitterness; others saw themselves as leading a wave of women advancing in important careers at NASA. Like Morgan, some of these women cracked the ceiling of leadership at the space agency. Early in the 1960s, for instance, Dr. Nancy Grace Roman headed the astrophysics division at NASA and oversaw such groundbreaking programs as the Orbiting Astrophysical Observatories. Others, such as Rhoda Hornstein, first worked at the Data Operations Branch of the Manned Flight Planning and Analysis Division at NASA Goddard Space Flight Center in suburban Maryland during Apollo and went on to other positions at NASA Headquarters. All of them recollect that they had to tread carefully, ignore various slights, and perform exceptionally well in a space agency that was very much a "man's world."

A graphic measure of this persistent problem occurred in 1992 when newly appointed NASA Administrator Daniel S. Goldin visited the Ames Research Center in the Bay area. Everyone at Ames remembers how Goldin embarrassed the Center's senior leadership by chastising it for the small number of women and minorities in senior leadership positions. During his first visit, Goldin saw around the conference table a collection of older white males and a number of younger and more diverse underlings sitting in perimeter chairs. He told the groups to change places. Goldin also dressed down Ames Director Dale Compton both for the lack of diversity and for the stodgy Ames way of doing things; Compton abruptly rose and left the room with tears in his eyes to collect himself while the meeting continued. Goldin realized he had gone too far at that point, but the lesson circulated through NASA like wildfire. The term, "stale, male, and pale," may not have originated with Goldin, but it became the match that lit a fire under NASA leadership in seeking much greater diversity in hiring and promotion. Everyone at NASA in the 1990s has a story about the excesses of Dan Goldin's leadership, and his record overall is far from stellar, but he deserves kudos for shaking NASA out of lethargy in terms of workplace diversity.

It would still take many years before a set of remarkably accomplished women and minorities would rise to the highest leadership levels at NASA. For example, Carolyn Leach Huntoon became the first woman to lead a NASA Center, recruited by Dan Goldin to serve as Johnson Space Center Director between 1994 and 1996 before moving to a White House science and technology policy position. She had been at NASA since 1970, working as a life scientist on Apollo and other human spaceflight programs. Her story may sound familiar: "There were individuals in the program that did discriminate, did make life hard for me and other women. Luckily, they moved on. I outlasted most of them. So I think the idea of women not being just like men, some people can't get over that."[9] Other women and minorities have served as Center Directors thereafter.

No woman has ever been named NASA Administrator, but in 2009 U.S. Marine Corps Major General and former astronaut Charles F. Bolden, Jr., became the first African American to take on the job, serving throughout the administration of Barack Obama. Earlier, Frederick Gregory, a former astronaut, was the first African American to serve as NASA Deputy Administrator, from 2002 to 2005, in the administration of George W. Bush.

Regardless of these changes, NASA has not been at the forefront of a positive diversity transformation in the workplace.

First Flights

Many observers felt tremendous excitement when Columbia, the first orbiter to be flown in space, took off from Cape Canaveral, Florida, on 12 April 1981, six years after the last American astronaut had returned from orbit. This first

Space Shuttle flight was led by veteran astronaut John W. Young—who first flew in the Gemini program and walked on the Moon during Apollo 16—and Robert L. Crippen, who transferred to NASA from the Air Force's military space program in the early 1970s. For this first flight—and the next three before being removed—the crew had ejection seats developed for the high-altitude, Mach 3-plus SR-71 reconnaissance aircraft. Bob Crippen commented that they were "primarily a placebo." He added, "There was a ton of flame from the solid rocket boosters. If you ejected, you would have to go through that and you would get very toasty."[10]

After about 2 minutes, at an altitude of 31 miles, the two boosters were spent and separated from the external tank. Waiting ships recovered them for eventual refurbishment and reuse on later missions. The spacecraft's three Space Shuttle main engines continued to fire for about 8 minutes before shutting down just as the orbiter reached space. As they did so, the external tank separated from the orbiter and followed a ballistic trajectory back to the ocean but was not recovered. Columbia reached a velocity on orbit of approximately 17,322 miles per hour, circling the globe in less than 2 hours. Once in orbit, Young and Crippen tested the spacecraft's on-board systems, fired the orbital maneuvering system used for changing orbits and the reaction control system engines used for attitude control, and opened and closed the payload bay doors. (The bay was empty for this first test mission.)

After two days in space testing Columbia, anticipation permeated the nation once again as it landed like an aircraft at Edwards Air Force Base, California. The first flight had been a success, and both NASA and the media ballyhooed the beginning of a new age in space exploration, one in which there would be inexpensive and routine access to space for many people and payloads. Speculations abounded that within a few years Shuttle flights would take off and land as predictably as airplanes and that commercial tickets might be sold for regularly scheduled "spaceline" flights.

NASA went on to build three additional reusable orbiter spacecraft in addition to Columbia. All were named after famous exploration sailing ships. Columbia (OV-102) commemorated one of the first U.S. Navy ships to circumnavigate the globe in 1836. Challenger (OV-099) was named for the Navy ship that made a prolonged exploration of the Atlantic and Pacific Oceans between 1872 and 1876. Discovery (OV-103) was named for two ships, the vessel in which Henry Hudson searched in 1610–11 for a Northwest Passage between the Atlantic and Pacific Oceans and instead discovered Hudson Bay and the ship in which Captain Cook visited the Hawaiian Islands and explored southern Alaska and western Canada. Finally, Atlantis (OV-104) was named after a two-masted ketch operated for the Woods Hole Oceanographic

Institution from 1930 to 1966 that traveled more than half a million miles in oceanic research.

Indicative of the broad expectations NASA had for the Space Shuttle, in 1983 it published a marketing brochure entitled *We Deliver* that touted the vehicle as "the most reliable, flexible, and cost-effective launch system in the world."[11] It suggested that the Space Shuttle would now engage in vigorous competition for commercial launch contracts with American Atlas, Delta, and Titan commercial launchers and the European Ariane launcher, and that NASA would go to extremes to ensure success in the marketplace.

Several of the early Space Shuttle missions were memorable. In spite of some difficulties, space science got something of a boost from the Shuttle since it could take into orbit large numbers of experiments. The boon to astrophysics, astronomy, life sciences, and materials research was often held up as important in the program. One of the most significant aspects of space science aboard the Space Shuttle was the use of "Spacelab," a sophisticated laboratory built by the European Space Agency, which fit into the cargo bay. The Shuttle also demonstrated something of its promised benefits in April 1984 when its astronauts retrieved, repaired, and reorbited the ailing Solar Max communications satellite. Even so, some scientists questioned the use of the Space Shuttle for scientific activities and suggested that the developmental costs could more usefully have been applied to expendable systems and robotic probes that promised higher scientific returns on investments.

There is no doubt that NASA greatly enhanced capabilities on orbit with the Space Shuttle. In its early years, the vehicle undertook a range of new and different activities. The Shuttle launched its first two commercial communication satellites on the STS-5 mission in November 1982 and followed this up through 1985 with the deployment of 24 communication satellites. At the time of the Challenger accident in January 1986, NASA had a backlog of 44 orders for commercial satellite deployments. But those missions did not always go as planned. For example, on STS-41B in 1984, the boost engines of both satellites to be deployed failed to fire properly, leaving the Palapa-B2 and Westar-6 communications satellites in useless low-Earth orbits. But the Shuttle offered another unique capability—one that could not be matched by an expendable vehicle—for retrieving those satellites. In November 1984, under contract to insurance companies, the Space Shuttle Discovery retrieved Palapa-B2 and Westar-6 and returned them to Earth. The insurance companies had already paid for the loss of the satellites, so both satellites were refurbished and resold to new customers; Palapa-B2 was launched in 1990 and operated until June 2005 and Westar-6 reentered service as Asiasat-1 in 1990 and operated until June 1999. This capability, as well as others, seemingly changed the nature of spaceflight in the future, as the Shuttle's promise found some realization.

In spite of the high hopes that had attended the first launch of Columbia in 1981, by January 1986 there had been only 24 Shuttle flights, and the vehicle was both less flexible and more costly to operate than envisioned. Missions were delayed for all manner of problems; observers began to criticize NASA for failing to meet the cost-effectiveness expectations that had been used to gain the approval of the Shuttle program 10 years earlier.

Critical analyses accepted by 1985 that the Space Shuttle effort had been both a triumph and a tragedy. The program had been engagingly ambitious and had developed an exceptionally sophisticated vehicle, one that no other nation on Earth could have built at the time. As such it had been an enormously successful program. At the same time, the Shuttle was essentially a continuation of space spectaculars, like Apollo, and its much-touted low-cost capabilities had not been realized. It made far fewer flights and conducted far fewer scientific experiments than NASA had publicly predicted.

The Challenger Accident

When the Challenger broke up on launch after the failure of an O-ring ignited an explosion in the external tank on 28 January 1986, it brought these earlier criticisms into focus. Not only were there many shortcomings of the Space Shuttle, but this failure resulted in the loss of seven astronaut lives. Although it was not the entire reason, the pressure to get the Shuttle schedule more in line with earlier projections throughout 1985 prompted NASA workers to accept operational procedures that fostered shortcuts and increased the opportunity for disaster. The explosion came 73 seconds into the flight, and astronauts Francis R. Scobee, Michael J. Smith, Judith A. Resnik, Ronald E. McNair, Ellison S. Onizuka, Gregory B. Jarvis, and Christa McAuliffe died in this accident, the worst in the history of spaceflight up to that time.

The accident, traumatic for the American people even under the best of situations, was made that much worse because the Challenger's crewmembers represented a cross section of the American population in terms of race, gender, geography, background, and religion. The explosion became one of the most significant events of the 1980s, as billions around the world saw the accident on television and identified with one or more of the crewmembers killed.

Several investigations followed the accident, the most important being the presidentially mandated blue-ribbon commission chaired by William P. Rogers. It found that the Challenger accident had resulted from a poor engineering decision: an O-ring used to seal joints in the solid rocket booster that was susceptible to failure at low temperatures. This component had been introduced into the Space Shuttle Program years earlier. Although Rogers tried to keep the Commission's analysis on a technical level, it also laid out a case for poor NASA management and internal communication. The possible failure of the solid rocket boosters' O-rings in cold weather had been understood by some program engineers prior to the accident. The Commission found that faulty communications systems and organizational "silos" of working-level engineers prevented the warnings from getting to leaders who could address the hazard. Some journalists went even further and explicitly made the case that NASA leaders knew of the O-ring problem but still pressed operations officials to launch so President Ronald Reagan could mention the flight in his State of the Union Address that evening.

There seems to be no evidence to support White House interference in the Challenger launch decision, but certainly the accident resulted from NASA's organizational patterns and technological decision-making process as much as from technical flaws in O-ring construction. Key NASA personnel were much more worried about other possible failings in the Shuttle system—especially with the Space Shuttle main engines—and spent most of their attention on those.

The fact that the seals had always done their jobs before contributed to a sense that they would not cause a major accident. The catastrophic failure that took place was a horrendous shock to the system at NASA, made all the more painful by their perception that the Commission scapegoated the Agency in assigning blame. There had been horrendous deaths in the NASA family, and the reviews showed that those deaths had been unnecessary. One could make the case that both the Challenger accident, and its official investigation, said as much about the Space Shuttle Program and the O-rings that allowed the explosion of the spacecraft as it did about the organizational culture that allowed them to go unaddressed.

Recovering from Challenger

With the Challenger accident, the Shuttle Program went into a 32-month hiatus while NASA worked to redesign the solid rocket boosters and revamp its management structure. NASA reviewed every aspect of this technology, making changes throughout the system, especially to the O-rings that had failed on STS-51L's solid rocket boosters. President Reagan brought back former Administrator James C. Fletcher (1971–77) to lead organizational transformation at NASA. Fletcher then appointed former Space Shuttle astronaut Richard H. Truly to take charge of the program, banking on the fact that an astronaut would be more committed to safety than someone who had not flown on the vehicle. Other personnel changes followed quickly thereafter, as NASA reinvested heavily in its safety and reliability programs, made organizational changes to improve efficiency, and restructured its management system.

The space agency also built a replacement orbiter for Challenger, Endeavour (OV-105), named for the first ship Captain Cook commanded on his voyage of discovery in the Pacific in 1768. Most important, NASA engineers completely reworked the components of the Shuttle to enhance its safety and added an egress method for the astronauts. A critical decision resulting from the accident and its aftermath—during which the nation experienced a reduction in capability to launch satellites—was to expand greatly the use of expendable launch vehicles.

When the Space Shuttle returned to flight operations with the launch of Discovery on STS-26 on 29 September 1988, it was a much safer vehicle than it had been before the January 1986 accident. The 15-year span of Shuttle operations thereafter was a "high-water" period in Space Shuttle missions. It witnessed a stunning record of achievement for the Space Shuttle as an operational vehicle and the astronaut corps as a remarkable cadre of pilots, scientists, engineers, researchers, and repair people. During this era, the Space Shuttle truly demonstrated what it could achieve in Earth orbit. At a fundamental level, the missions flown during this period of operations swept away the vestiges of orbital space as a frontier and turned it into a normal realm of human activity.

The Shuttle/Mir Program

One of the central activities of the Space Shuttle in the 1990s involved a series of missions to the Russian Mir space station, originally launched in 1986. As a precursor to a larger post–Cold War effort to build an International Space Station, NASA officials and leaders from the Russian Space Agency determined to undertake in the mid-1990s nine Shuttle flights to Mir, in addition to five medium- to long-duration flights on Mir by U.S. astronauts. This cooperative effort led directly to the February 1994 flight of cosmonaut Sergei Krikalev on STS-60 and continued in February 1995 when Discovery rendezvoused with Mir during the STS-63 mission with cosmonaut Vladimir Titov aboard.

This served as the prelude for the first mission by Atlantis to reach Mir in July 1995 and ushered in an era of regular rendezvous, docking, crew transfers, and supplies and equipment deliveries. These groundbreaking flights paved the way toward assembly of the International Space Station beginning in November 1998. Atlantis lifted off on 27 June 1995 from Kennedy Space Center's Launch Complex 39A with a unique 5-minute launch opening to meet Mir in orbit for STS-71. It proved difficult to launch during such a narrow window, but it

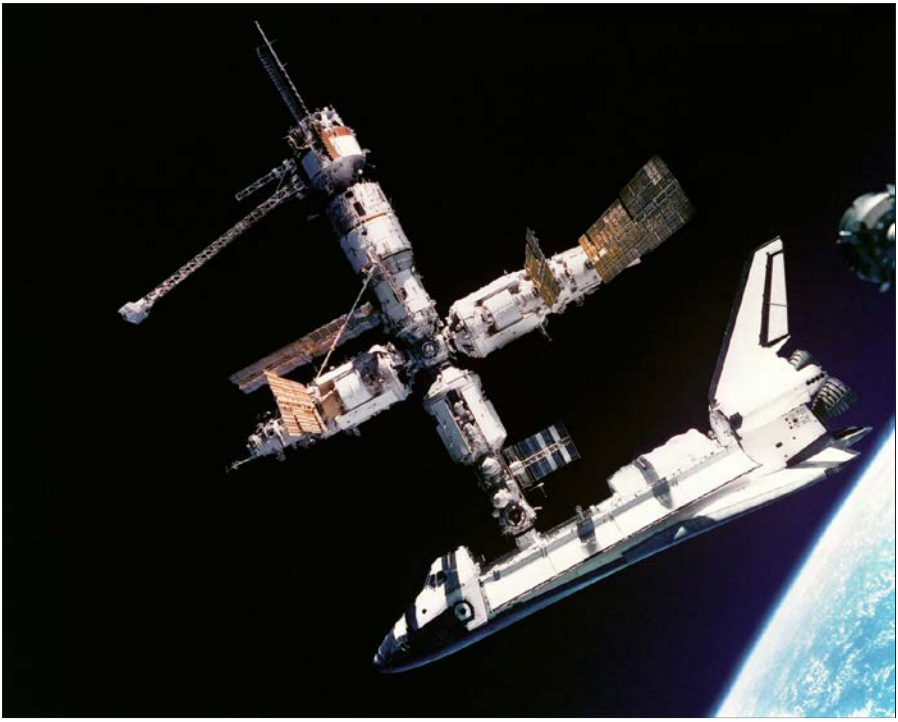

Figure 8-4. The Space Shuttle Atlantis is docked to the Mir space station on 4 July 1995. Cosmonauts Anatoliy Solovyev and Nikolai Budarin took this photograph while temporarily undocked from Mir in their Soyuz spacecraft during a fly-around of the Russian station. (NASA,STS071(S)072)

went off without a hitch. For the next two days after launch, periodic firings of Atlantis's orbital maneuvering rockets gradually brought the orbiter to closer proximity with Mir. When Atlantis docked with Mir on 29 July, it was perhaps the most significant event in the history of spaceflight since the symbolic joining of the American Apollo and the Soviet Soyuz spacecraft 20 years earlier. It also signaled a new age of cooperation in space, where exploration of the universe would be measured more in terms of what a coalition of states could accomplish rather than what a single nation did.

Additional astronauts, often ferried to and from Mir on the Space Shuttle, worked with the Russians on its space station until 1998. In all, NASA undertook nine Shuttle docking missions to Mir between 1995 and 1998. For most of their time aboard Mir, the experience proved routine. Shannon Lucid, as an example, spent a seemingly idyllic time aboard Mir in 1996, undertaking daily scientific experiments. She recalled that she had considerable time to read, brushing up on Charles Dickens. This changed when a succession of failures on

Mir in 1997, including a fire, spelled an end to the cooperative program after nine Space Shuttle docking missions.

So what do these Shuttle missions to Mir mean? The significance seems to rest on the international context of the docking missions and what they signal for the future of spaceflight. Humans several hundred years hence may well look back on these flights as the tangible evidence of the beginning of a cooperative effort that was successful in creating a permanent presence for Earthlings beyond the planet. It could, however, prove to be only a minor respite in the competition among nations for economic and political supremacy. The most important thing to remember about it, perhaps, is that the future is not yet written and that humans in the "here and now" have the unique opportunity to support and contribute to the success of an international space station, an outpost that will serve as a base camp to the stars and enable the move from this planet to a wide universe beyond.

The Loss of Columbia and the End of the Space Shuttle Program

NASA personnel and leaders had a celebration planned on 1 February 2003 for the return of Columbia and its crew after the successful completion of STS-107. STS-107 had been launched from the Kennedy Space Center's Launch Complex 39A on 16 January on a science mission that was dedicated to research in physical, life, and space sciences. It held the Spacelab Research Double Module and involved the execution of approximately 80 separate experiments, composed of hundreds of samples and test points. The seven astronauts aboard had worked 24 hours a day, in two alternating shifts, to complete these experiments.

Unfortunately, STS-107 never made it home; both the vehicle and crew were lost during reentry into Earth's atmosphere. NASA lost communication with Columbia a little before 9:00 a.m. EST on 1 February, and when the Shuttle failed to land at its appointed time of 9:16 a.m. at the Kennedy Space Center, NASA Administrator Sean O'Keefe knew something was wrong. He said:

> I immediately advised the President and the Secretary of Homeland Security, Tom Ridge, at the point after landing was due to have occurred at 9:16 a.m., and spoke to them very briefly to advise them that we had lost contact with the Shuttle orbiter, Columbia, and STS-107 crew. They offered, the President specifically offered, full and immediate support to determine the appropriate steps to be taken. We then spent the next hour and a half working through the details and information of what we have received [concerning]…operational and technical issues.[12]

Columbia was the first orbiter built and flown in space; having undertaken 28 successful missions, it had an anticipated service life of 100 flights.

The Columbia Accident Investigation Board (CAIB) found that at approximately 81 seconds after a 10:39 a.m. EST launch on 16 January 2003, foam from the external tank left bipod ramp area impacted Columbia in the vicinity of the lower left-wing reinforced carbon-carbon (RCC). During reentry on the morning of 1 February 2003, superheated gases entered Columbia's left wing where holes existed, destroying the aluminum superstructure. The spacecraft broke up, and the entire crew perished in the accident.

Again, NASA grounded the Shuttle fleet, worked to understand the technical problems, made repairs, and returned to flight in May 2006. Meantime, the President directed in January 2004 that the space station would be completed, and the Space Shuttle retired. NASA would then move on to another vehicle for orbital and deep space exploration. In the end, the Space Shuttle flew several additional missions, serviced the Hubble Space Telescope, and ceased operations in 2011.

Legacies

When assessing the 30-year history of the Space Shuttle's operational life, one must first acknowledge that it was an important symbol of the United States' technological capability, universally recognized as such by both the American people and the larger international community. NASA's Space Shuttle remains after two and a half decades one of the most highly visible symbols of American technological capability worldwide. Even critics of the program, such as journalist Greg Easterbrook, acknowledge this. As he wrote in *Time* just after the Columbia accident:

> A spacecraft is a metaphor of national inspiration: majestic, technologically advanced, produced at dear cost and entrusted with precious cargo, rising above the constraints of the earth. The spacecraft carries our secret hope that there is something better out there—a world where we may someday go and leave the sorrows of the past behind. The spacecraft rises toward the heavens exactly as, in our finest moments as a nation, our hearts have risen toward justice and principle.[13]

Easterbrook appropriately characterized the sense of wonder and awe that the Shuttle evoked around the world.

The Space Shuttle became an overwhelmingly commanding symbol of American technological virtuosity for the world community. Ask almost anyone outside the United States what ingredients they believe demonstrate

Figure 8-5. Orbiting Earth at an altitude of 356 nautical miles, the Space Shuttle Endeavour's Remote Manipulator System (RMS) holds astronaut F. Story Musgrave during a servicing mission to the Hubble Space Telescope in December 1993. Jeffrey A. Hoffman is in the payload bay. They are about to wrap up the final of five extravehicular activities (EVAs). The west coast of Australia forms the backdrop. (NASA, STS061-48-001)

America's superpower status in the world, and they will quickly mention the Space Shuttle—as well as NASA's larger space exploration program—as a constant reminder of what Americans can accomplish when they set their minds to it.

Second, the Space Shuttle was an undeniably remarkable machine, but one with a mixed legacy. No other nation on the face of the Earth had the technological capability to build such a sophisticated vehicle during the 1970s. Few could do so today. A massively complex system—with more than 200,000 separate components that must work in synchronization with each other and to specifications more exacting than any other technological system in human history—the Space Shuttle must be viewed as a triumph of engineering and excellence in technological management. As such, it has been an enormously successful program. The research, development, and operation of the Space Shuttle represent a worthy follow-on to the spectacularly successful Apollo program of the 1960s and early 1970s.

Third, the Space Shuttle proved to be a flexible space vehicle. Most assuredly, the range of possibilities for operations on orbit expanded dramatically with the launch of Columbia in 1981. The ability to carry a diversity of payloads, to accomplish a myriad of tasks on orbit, and to deploy and retrieve satellites are attributes that need to be considered in any effort to develop a follow-on system. A successor to the Space Shuttle should approach a similar level of flexibility that this vehicle has demonstrated, and it is important to consider the uniqueness of the orbiter's capabilities in planning for the future.

Fourth, the Space Shuttle served as a fine test bed for scientific inquiry. While the program was not conceptualized as a science effort—rather it was a technology demonstrator and workhorse for space access—it was used as an exemplary platform for all manner of microgravity and space science enterprises. The Space Shuttle's 135 missions into Earth orbit allowed a wide range of scientific experimentation.

Finally, the Space Shuttle Program, while an enormous achievement, has clearly wrought a divided legacy for NASA. As a symbol of American technological excellence and as the launch system for NASA's astronaut corps, it received high marks. But the program failed to achieve its core objective: lowering the cost of reaching Earth orbit. In fact, President Nixon stated in 1972 that the Shuttle's "resulting economies may bring operating costs down as low as one-tenth of those present launch vehicles."[14] Granted, this was an extraordinarily elusive goal, but disappointment over not achieving it has plagued NASA and brought cynicism from the public for a wide array of U.S. space efforts. Cost control remains a goal that must be emphasized in the development and operation of any new human launch vehicle.

CHAPTER 9

NASA's First "A" in an Age of Spaceflight

The engines roared as the tiny research plane headed up, dark shadows in the cockpit contrasted with an intensely brilliant sky outside. NASA research pilots such as Joe Walker pushed these vehicles to extremes never experienced before. On one flight, Walker reached the edge of space in the X-15 research plane. As the powerful rockets pushed him back into his couch, he shouted "Oh, my God!" His flight controller jokingly responded, "Yes? You called?" That exchange became famous in NASA.[1]

Each time, Walker and others realized that there was a whole world below, one that they would return to once the mission objectives had been met. He, like every other research pilot working at NASA, followed mission requirements meticulously, performing as required, slowing as needed, and setting down on the Muroc Dry Lakebed. Emerging from these vehicles, every pilot opened their helmets and breathed air again, deeply. As always, the adrenaline rush of the flight balanced with a thankfulness for returning safely and the satisfaction of a job well done.

These experiences have been repeated many times by many different research pilots since the transformation of the NACA into NASA. Whereas aeronautical research had been the *sine qua non* of the NACA, it was one among several other high-profile missions for NASA from the late 1950s to the present. A continuing story of excellence among the aeronautics research centers of NASA has gone little noticed over the years as most Americans equate NASA only with spaceflight. That first "A" in the acronym for NASA, however, is quite significant. Aeronautics research has enabled the advance of speed and altitude, but also efficiencies in operations and technologies, greater flight safety, and a host of other accomplishments. One could point to a range of accomplishments from the advanced turbofan to the glass cockpit as examples of contributions by NASA to aeronautics.

Transformations

When the NACA became NASA, the organizations that were still charged with aeronautical research underwent a transformation every bit as striking as the reorganization that made the great successes in spaceflight of the 1960s possible. First, the NASA budget grew rapidly but aeronautics received an ever-smaller percentage of the total Agency allocation. This meant, by extension, that NASA leaders paid a shrinking amount of attention to aeronautical research as time passed. Even so, because of the overall growth in the NASA budget, greater opportunities existed than ever before. Those had to be seized by aerodynamics, materials, propulsion, electronics, and other types of engineers.

Second, as the years passed, policy-makers came to believe that aeronautics had matured sufficiently that it no longer required federal investment to assure cutting-edge capabilities. For example, in 1982 a multi-agency review of national aeronautical policy considered two key 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?

In answer to these questions, the report noted that while the aerospace industry was no longer a backwater as it had been when the NACA was created, it still required serious efforts to advance the technology and that no major alteration to the then-current structure of the research and development (R&D) system was required.

At the same time, NASA's aeronautics program achieved a measure of success through the continuation of many of the same types of activities that the NACA had pioneered in the immediate post-war period. For example, it developed to a high degree large cooperative R&D projects reminiscent of the early X-plane series. Always these had multiple partners and often achieved astounding results. The X-15 program of the latter 1950s and 1960s, the lifting-body research program of the 1960s and 1970s, and the later National Aerospace Plane and X-33 technology demonstrator exemplify this type of work.

In addition to those efforts, NASA's research to achieve efficient and safer aircraft led to several truly remarkable breakthroughs. For example, NASA's digital fly-by-wire program, its advanced turboprop engine design, its "glass cockpit" of advanced avionics, its wind shear research, and a host of other projects achieved marked success. Collectively, these efforts transformed aviation by the turn of the 21st century.

Figure 9-1. X-15 ship #3 (56-6672) is shown in flight over the desert in the 1960s. This spaceplane made 65 flights during the program, attaining a top speed of Mach 5.65 and a maximum altitude of 354,200 feet. (U.S. Air Force)

Finally, NASA engineers developed new infrastructure supporting a range of aviation activities. Two potential areas abounded. First, the investment in computing power made possible radical new capabilities in aircraft design. Computational fluid dynamics served to make possible the transition of R&D from the longstanding reliance on wind tunnels to computer simulations for verifying performance. This had the added advantage of allowing NASA to close several of its wind tunnels since they were no longer necessary and to transition workload and investment costs to other arenas. While some engineers, especially those affectionately known as "tunnel rats," lamented this change, it meant that the Agency could accomplish more than in the past for lesser costs. Similarly, such innovations at NASA as the Massively Parallel Processor (MPP) advanced computer technologies for all manner of purposes, and this also found expression in the aeronautics research program.

Second, efforts to enhance the capabilities of the airways and air traffic control systems of the United States greatly altered for the better the manner in which flight was accomplished. Redesign of navigational, communication, and other systems tightened the system so that greater numbers of aircraft could be managed at any given time. Traffic management and overall airways structure changed in relation to these new capabilities.

As NASA matured in the 1960s, most of the aeronautics R&D programs continued in a way not dissimilar to that of the NACA. The NACA primary Centers—Ames Research Center in the Bay area of California, Langley Research Center in Hampton, Virginia, and Lewis (now Glenn) Research Center in Cleveland, Ohio—carried out the majority of all aeronautical research. In every case, they got involved in spaceflight to a greater or lesser extent but remained focused on aeronautics. The Flight Research Center at Muroc Dry Lake in California, now the Armstrong Flight Research Center, continued its focused research and tests but added space test operations to its portfolio as well.

For more than five decades, NASA aeronautics leaders pursued cutting-edge aeronautics research, but in the 1970s and 1980s the focus shifted somewhat from the earlier higher, faster, farther approach to one that aeronautics leaders referred to as also “smarter.” This effort included ultra-green flying through reduced noise, air, and other types of pollution; attempts to lessen the boom in supersonic flight; developing ever-more-capable robotic aircraft; and harnessing advances in computers, electronics, and robotics to innovate aircraft. For example, during the early 1970s NASA established the Aircraft Energy Efficiency Program to build more fuel-efficient aircraft. With the saturation of the airways, NASA worked on both short takeoff and landing aircraft and air traffic control systems. At the same time, the rise of digital computing allowed NASA the opportunity to enhance control systems through digital fly-by-wire technology that has proved critical for several unusual and remarkably successful aircraft designs.

Into the 1990s, NASA’s aeronautics research program not only involved what had immediately presaged it but also expanded to large programs reminiscent of spaceflight projects such as the Advanced Subsonic Technology (AST) Program and the High-Speed Research (HSR) Program. A significant downturn in the NASA aeronautics budget in the first decade of the 21st century forced NASA’s aeronautical leadership not only to restructure existing programs but also to place on hiatus most new research initiatives. For example, NASA’s aeronautics budget was just over $1 billion in fiscal year (FY) 2004; it declined to $884 million in 2007 and to $724 million in 2008. That represented a funding reduction of 32 percent over three years. The NASA aeronautics R&D budget in 2014 stood at $566 million out of a $17.7 billion dollar budget. In the recent past, especially with the rise of new technologies such as drones, political leaders have recognized the need to enhance aeronautics funding once again. In FY 2021 the White House proposed $819 million to support research into future commercial and military aviation, supersonic commercial aircraft, and robotic traffic management.

Early Hypersonic Flight Research

The success of NASA's X-15 program in the 1960s led directly to longstanding efforts to advance hypersonic flight—speeds greater than Mach 5—thereafter. Even as the X-15 program proceeded in the 1960s, the U.S. Air Force investigated the possibilities of a single-stage-to-orbit spaceplane that could take off horizontally and fly to a 300-mile orbit before returning to Earth and landing like an aircraft. The X-15 results fed directly into this program, called the Recoverable Orbital Launch System (ROLS). The ROLS propulsion system collected air from the atmosphere, then compressed, liquefied, and distilled it to make liquid oxygen, which mixed with liquid hydrogen before entering the engines. NASA played a key role in this complicated propulsion system, named LACES (Liquid Air Collection Engine System), later renamed ACES (Air Collection and Enrichment System), as well as various other engine concepts. Faced with the uncertainties of this technology's success, after several years of R&D this spaceplane died in the Department of Defense.

NASA continued research on the propulsion technology thereafter, furthering scramjet propulsion technology viewed as necessary to the successful development of a hypersonic vehicle. Rather than a pure rocket engine, scramjets had much in common with jet aircraft engines. Incapable of functioning below the speed of sound, the scramjet name is a truncation of *s*upersonic *c*ombustion *ramjet*. Ramjets are jet engines that propel aircraft at supersonic speeds by igniting fuel mixed with air that the engine has compressed. Scramjets are ramjets that achieve the same objective at much higher hypersonic velocities. Supersonic air would enter the front of the ramjet and automatically would be compressed. By careful shaping of the inlet duct, one could achieve enough compression to sustain combustion simply from the vehicle's forward velocity. This compressed air would then be mixed with fuel in the combustion chamber and ignited, causing the resulting gases and energy to be expelled out of the back to provide thrust.

At the Langley Research Center engineers designed and built their first scramjet with the intention of verifying the basic theory behind hypersonic propulsion under the auspices of the X-15 research effort. NASA's Hypersonic Ramjet Experiment (HRE) intended to utilize the X-15 as a test bed. Beginning in the early 1960s, Langley engineers worked with researchers at NASA's Flight Research Center to extend the X-15's speed capabilities, perhaps even to Mach 8, by adding a scramjet fueled from jettisonable drop tanks protected by a revolutionary thermal protection system.

NASA engineers championed modifying one of the X-15s as a Mach 8 research vehicle that could be tested with a scramjet fueled by liquid hydrogen.

Figure 9-2. Before he became a world-famous astronaut, Neil Armstrong was the epitome of the "right stuff" as a research pilot for NASA's High Speed Flight Research Center. Here he is seen in the cockpit of the X-15 ship #1 (56-6670) after a research flight in 1961. (NASA, ECN-89)

The proposal became more attractive when a landing accident involving the second X-15 in November 1962 forced the rebuilding of the aircraft. In March 1963, the Air Force and NASA authorized North American Aviation, Inc., to rebuild the aircraft with a longer fuselage, a modified propellant system, two external drop tanks, and a small tank for liquid hydrogen. The liquid hydrogen tank would power a small scramjet engine attached to the ventral. The drop tanks could be recovered via parachute and refurbished.

North American Aviation delivered the modified X-15A-2 in February 1964. This craft first flew in June 1964, piloted by Major Bob Rushworth of the U.S. Air Force. After a shakedown and a significant number of nonhypersonic flights, in November 1966, Air Force pilot Pete Knight set an airspeed record of Mach 6.33 in the plane. NASA then grounded it for application of a thermal ablative coating to enable it to exceed Mach 7 without being destroyed by friction in the air.

By the summer of 1967, the X-15A-2 was again ready for flight, this time with the appropriate ablative coating. The weight of the ablative coating—125 pounds higher than planned—reduced the theoretical maximum performance of the airplane to Mach 7.4, but it was still a significant advance over the Mach 6.33 previously attained. This vehicle proved visually striking; it had a flat off-white finish and huge external tanks painted a mix of silver and orange-red with broad striping. On 21 August 1967, Pete Knight completed the first flight in the vehicle, reaching Mach 4.94 and familiarizing himself with its handling qualities. His next flight, on 3 October 1967, was destined to be the X-15's fastest flight. It proved a stunning but ultimately disappointing sortie. Knight reached a maximum speed of Mach 6.7 and an altitude of 102,100 feet. But it also was the last flight of the X-15A-2 because of extensive thermal damage to the vehicle.

NASA research pilot Milton O. Thompson commented on how this flight ended the Mach 7 initiative:

> A shock wave off the dummy ramjet interacting with the boundary layer caused severe localized heating that burned off all the ablator and burned through the basic Inconel ventral fin structure. We almost lost the airplane. We took too big a step. We essentially went from Mach 5 to almost Mach 7 in one step with the dummy ramjet. The moral is that even though we supposedly checked out each individual configuration, we should have put them all together and again worked up incrementally in Mach number. We would thus have appreciated the significance of the shock impingement heating problem.... [Dryden has] been in the flight-research business over twenty-seven years. Many of the people who worked on the X-1s are still here, and yet we still occasionally get caught short. We seldom get caught on the same problem, but it seems that we never run out of new problems.[2]

This event, NASA research pilot Bill Dana remarked, "was the death knell for the entire project. Program management decided not to fly the X-15A again and to fly the X-15 No. 1 only for calendar year 1968."[3] After the flight, NASA sent the X-15A-2 to North American for repair, but it never flew again. It is now on exhibit—in natural black finish—at the Air Force Museum, Wright-Patterson Air Force Base, Ohio.

Because of these flights, despite the loss of the X-15-2A, hypersonic aerodynamics became a field broader than just its theoretical foundation. But even so, the flight research data are scant. The X-15 surpassed Mach 6 on only four occasions, the majority of its 199 flights being in the Mach 5 to 5.5 range. Yet what successes it did achieve point to the possibilities inherent in a well-designed, Mach 6-plus vehicle to travel around the globe in only a few hours. Likewise, scramjet research developed only modestly thereafter. Moreover, it cannot go much farther, despite advances made in laboratories, until the nation develops an air-breathing power plant "testable" on a flight research vehicle. Since the abrupt end of the X-15 program in 1968, an ever-increasing number of experiments requiring a hypersonic test bed have been added to the list of projects left to be done. Since the X-15 quit flying, NASA engineers have consistently sought to return to this research, becoming involved in several subsequent programs that either did not quite get to the hardware stage or only briefly so in one-off tests.

NASA's Lifting-Body Program

Also during the 1960s, NASA pursued the lifting-body research program at NASA's Flight Research Center. Between 1963 and 1975 NASA developed, built, and flew a succession of ever-more sophisticated wingless vehicles—M2-F1, M2-F2, M2-F3, HL-10, X-24A, and X-24B—known as lifting bodies because their particularly aerodynamic fuselage produced all the lift needed. This research originated in the mind of NACA engineer Alfred J. Eggers, Jr., in 1957, when theoretical work suggested that wings were a hindrance for very-high-speed flight and that the entire vehicle could generate all the lift necessary while reducing drag.

In 1962 the Flight Research Center Director, Paul Bikle, approved a small in-house research program to build a lightweight, unpowered lifting body, which soon became affectionately known as the "flying bathtub." The initial plywood lifting body, M2-F1, was towed behind a Pontiac convertible purchased by a NASA engineer and then "souped-up" to drag the aircraft as fast as 120 mph across Rogers Dry Lake. It flew and produced enough flight data to proceed with additional tests behind a NASA tow plane to altitudes of 12,000 feet.

Following this success, NASA next developed the M2-F2 and the HL-10, both built under contract by the Northrop Corporation. Other vehicles followed, some reaching speeds with rocket propulsion of up to 1,220 mph and altitudes of more than 90,000 feet. Between 1970 and 1972, the M2-F3 flew more than 25 missions; it was one of the most successful of the lifting-body designs. The last of the lifting bodies was the X-24B, again flying high and fast and collecting considerable aeronautical data. Data from all of these aircraft were factored into the design of the Space Shuttle then under development by NASA. These investigations also factored into the design of theoretical hypersonic flight vehicles in the years since.

Hypersonic Research: Round Two

More than three decades after NASA's first entrée into hypersonic aeronautics research, it reentered the field in a spectacular way with a partnership with the Department of Defense to develop the National Aero-Space Plane (NASP). Originated in the early 1980s, NASP had many purposes, some military and some not. Fueled by the realization that the Space Shuttle could never live up to its early expectations, NASA leaders argued for the development of this single-stage-to-orbit (SSTO) hypersonic spaceplane that could take off and land on runways. With the beginning of the administration of Ronald Reagan, and its associated military buildup, the Defense Advanced Research Projects Agency (DARPA) began work on a hypersonic vehicle powered by a hybrid integrated engine of scramjets and rockets as a "black" program code-named "Copper Canyon."

After several years of classified work, in 1986 the Reagan administration unveiled NASP, also designated the X-30, as "a new Orient Express that could, by the end of the next decade, take off from Dulles Airport and accelerate up to 25 times the speed of sound, attaining low earth orbit or flying to Tokyo within two hours."[4] NASA loved the idea and partnered with DARPA on the X-30, even though NASP never achieved anything approaching flight status. It finally fell victim to budget cuts in 1992, in part as a result of the end of the Cold War. But it also ended because of its technological overstretch. By the time of its cancellation in 1992, the government had admitted to making a $1.7 billion investment in the National Aero-Space Plane, but parts of the R&D were highly classified, and there were probably additional expenditures. NASA has followed this effort with additional hypersonic research efforts to the near present. All of those, memorably, were intended as Space Shuttle replacement vehicles, although none came to fruition.

Improving Research Tools

As NASA entered the digital era of the 1970s, it began to harness new capabilities to further aeronautical research. One of the most revolutionary ideas involved the development of computational fluid dynamics (CFD), which allowed aerospace engineers to transform R&D from the costly, demanding, exacting, and time-consuming wind tunnel–fixated process to a computer-aided process that allowed much more efficient and productive work. CFD aided the processing of Navier-Stokes equations that described fluid motions generating lift and drag on a wing. Since the first studies of these problems in the 19th century, the exacting process of calculating Navier-Stokes equations had been so complex and time-consuming that aerodynamicists had great difficulty applying them efficiently to aircraft design. Engineers using linear equations—two-dimensional (2D)—could go only so far. The solving of many variables using multiple equations concurrently required greater computational power than was available in the predigital age.

Engineers at Ames Research Center had long been working to streamline the process of resolving the problem of Navier-Stokes equations. An early key figure at Ames was Harvard Lomax, who started experimenting with electronic computers from the late 1950s into the 1970s, using them to model the behavior of blunt-body objects. By 1976, the possibilities of CFD had progressed sufficiently for Ames Research Center Director Hans Mark to set up a group under engineer F. Ronald Bailey to advance the concept. Using the most powerful computers available—at the time the Cray-1 supercomputer—Ames researchers began to break down the equations into usable subparts and establish methodologies for resolving multiple variables concurrently. Three years later Ames formed the Numerical Aerodynamic Simulator (NAS) Projects Office with the specific objective of advancing CFD capabilities. Later, Ames also put a Cray X-MP and a Cray-2 to use for CFD analysis. Research activities at other NASA Centers also helped to transform the entire field. During this process the ILLIAC IV became the first massively parallel computer; it found significant use in advancing CFD capabilities at Ames Research Center and elsewhere.

Some friction quickly emerged between traditionalists who had a strong commitment to wind tunnel testing and the emerging capabilities of computational fluid dynamics. Early on, NASA's "tunnel rats" resented the rising amount of funding invested in CFD research, money that they believed could be effectively used for wind tunnel work. Only with efforts to make sure that equitable funding existed—and with the training of wind tunnel personnel in CFD techniques—did this begin to change. Over time, it became obvious that CFD provided great capabilities to resolve Navier-Stokes equations, but that wind tunnels were necessary to validate CFD findings. Always, users found that for all the great capabilities of CFD, at some point there also has to be demonstration of solutions in the real world. Wind tunnels, often exceedingly small ones that used tiny models, were ideal for that purpose.

CFD began to pay off in the late 1970s, with the successful redesign of the wing for the HiMAT (Highly Maneuverable Aircraft Technology) flight test vehicle, a ⅓ scale model of a fighter plane used to test new aerodynamic and control concepts. CFD techniques were also key to the successful retrofitting of the engines on the Boeing 737, making it one of the most successful passenger airliners in history. Using data from CFD studies, Boeing engineers were able to design the new fanjets for the engines for much greater efficiency.

By the 1990s, the success of CFD had made obsolete many of the older wind tunnels dating from the NACA era. Accordingly, NASA moved to close several at various centers. Not all of them by any means, but those closed signaled the end of an era. NASA leaders justified these closings by highlighting other capabilities available, such as CFD. Several wind tunnels closed easily and without issues; other closures generated controversy. NASA transferred the National Full-Scale Aerodynamic Complex (NFAC) to the U.S. Air Force and closed the 12-Foot Pressure Wind Tunnel at Ames in 2003 because a decline in users meant that the facilities failed to pay operational costs.

No wind tunnel closing generated more controversy than the Full-Scale Wind Tunnel at the Langley Research Center. A venerable wind tunnel with a long history of outstanding research going back to the 1930s—and it was designated a National Historical Landmark in 1985—by the 1990s users had so declined that NASA was unable to continue supporting its operation. First NASA negotiated to allow Old Dominion University to use it on a commercial basis, which led to such interesting projects as testing the aerodynamics of racing cars. Even this, however, failed to salvage the tunnel. Reluctantly, after documentation of its history and architecture, the Langley Full-Scale Wind Tunnel was demolished in 2010.

At sum, the story of CFD is essentially a story of new tools/new discoveries. At the same time it is the story of the creation of obsolescence in the tools formerly so significant to aerospace research and development. The same has been true throughout history. For example, there was a time when wagon makers existed around the globe. In the 20th century virtually all of them went out of business as their efforts became outmoded with the rise of the automotive industry. Closer to home for aerospace engineers, there was a time when those working in the field would not be without their slide rules at their side. As electronic means of calculation advanced, few today continue to use them, and in some cases aerospace engineering students are not even taught how to do so.

NASA also pursued the development of the Massively Parallel Processor (MPP) to aid in scientific and technical computation. During the middle part of the 1970s engineers at NASA's Goddard Space Flight Center developed the MPP to see if parallel computing power could be yoked to satisfy NASA's anticipated vast space and Earth science computing needs. In particular, scientists wanted to analyze the long-duration, and quite extensive, imagery available from Landsat. Without greater computational power this desire could not be met. NASA contracted with the Goodyear Aerospace Corporation in 1979 to see how many processes could be undertaken simultaneously. This was the first instance in which anyone had attempted such a high degree of parallelism. Goodyear delivered the MPP to Goddard in May 1983.

Throughout this process, however, Ames Research Center remained the Agency's center for supercomputing. And massively parallel processing is not just the standard for computing power at NASA, it's a standard in the field of supercomputing itself. By 1985, 39 investigators had organized into a cadre of practitioners, and a year later these same investigators presented papers on their work at the first symposium on the Frontiers of Massively Parallel Scientific Computation. These papers and a subsequent report written by the leaders of the program documented the wide variety of applications that could effectively be processed on the MPP's architecture.

Through this effort, by 1990, the MPP had been established as a viable and effective technology for satisfying the previously overwhelming computational needs of aerospace science and technology. Thereafter the technologies pioneered by the MPP have been advanced, made faster, and rendered more capable than ever before. MPP has become the standard for computing power at NASA.

Going Digital

As impressive as computational fluid dynamics and massively parallel processor technology were for research purposes, digital computational capabilities also found significant applications in guidance and control of the air- and spacecraft developed through NASA's efforts. Many successes resulted; only three of the more spectacular are recounted here. One of the great successes in this arena has been the development of digital fly-by-wire (DFBW) technology. The DFBW program originated at NASA in the late 1960s as a means of replacing conventional hydraulic and mechanical flight controls on an aircraft with an electronic control system. Flight controls, rather than being linked to the control surfaces of the flight vehicle, were converted to electronic signals transmitted by electrical wires—therefore fly-by-wire—between the pilot and the exterior of the plane. In such a system, computers took over much more of the control functions of the aircraft and could fully control the vehicle through automatic signals.

The Dryden (now Armstrong) Flight Research Center led this effort, building on pioneering efforts in fly-by-wire control developed for its lifting-body program and the Lunar Landing Research Vehicle of the 1960s. NASA engineers led by Kenneth Szalai took a suggestion from Neil Armstrong, who had experience with earlier efforts and modified an F-8 fighter aircraft to test DFBW conceptions beginning in 1976 and continuing for nine years thereafter with 211 F-8 flights. Through this and other research efforts, the insertion of computer technology managing electronic flight controls replaced large bundles of mechanical and hydraulic connections on all aircraft everywhere in the world.

Figure 9-3. F-8 digital fly-by-wire (DFBW) aircraft in flight over snowcapped mountains. Although it is externally identical to a standard Navy F-8C, this aircraft had its control system replaced by an Apollo digital computer and other maneuvering electronics to document the superiority of this type of system. (NASA, ECN-3478)

As a second example, NASA worked during the 1970s and 1980s to develop the most efficient aircraft engine imaginable, the advanced turboprop. This program originated in 1976 at NASA's Lewis (now Glenn) Research Center as a means of addressing the need to reduce fuel consumption costs during the height of the energy crisis of the 1970s. NASA undertook six separate projects to improve aircraft fuel efficiency, some of them relatively simple and others more complex. The Advanced Turboprop Project promised the greatest payoff but was also the most technically demanding.

NASA engineer Daniel Mikkelson, working with others, pursued swept propeller blades to reduce noise and increase efficiency, generating a patent. Other aspects of this research led to better fuel management using computing technologies. The advanced turboprop project received the Robert J. Collier Trophy for outstanding achievement in aerospace for 1987. While the energy crisis had abated by the time that the program was terminated, knowledge gained from this effort has found its way into later aircraft engine designs.

Finally, NASA researchers also worked to perfect the so-called "glass cockpit" in the 1980s and 1990s. Replacing the longstanding mechanical instruments of the flight deck, the glass cockpit featured digital displays on LCD screens to communicate the standard information—altitude, rates of climb or descent, power settings, airspeed, navigation, and the like—as an integrated flight management system. The technology greatly simplified aircraft operation and navigation and allowed pilots greater flexibility and ease of understanding about what was taking place on the aircraft. The design eliminated complexity, increased efficiency, and reduced costs. Every large aircraft built since the 1980s has employed this technology and increasingly, smaller aircraft include it as well.

NASA's role in the development of this technology took several forms. First, researchers sought to reduce the number of instruments on a flight deck—some larger aircraft had more than 100—and digital technologies on a screen allowed the multitasking of individual components. NASA's research on displays led to the creation of an integrated, easily mastered flight profile, what has come to be known as aircraft "situational awareness." NASA then used a Boeing 737 test bed at the Langley Research Center to undertake a series of flights to prove the concept. It was successful beyond all expectations, although it took some time to convince aircraft manufacturers to adopt it because of the costs of transition. Since before 2000, however, all have acknowledged the great benefits of this new technology, and it is now ubiquitous in the industry.

Making Airways Safer

The NACA/NASA has been long involved in efforts to increase the safety and efficiency of aircraft. Some of those efforts have been stunning in their application of complex technology. Others have been remarkably mundane. Three that are recent efforts include the grooved runways now ubiquitous in the industry, wind shear detection systems pioneered in the 1990s, and airways control systems.

Two airline accidents in January 1982—an Air Florida 737 crash into the 14th Street Bridge after departing from Washington National Airport and a World Airways DC-10 crash at Boston's Logan Airport—due to winter/icy conditions prompted a public outcry and pressure from Washington politicos to examine runway safety. NASA and the Federal Aviation Administration (FAA) accordingly received a mandate to study the "reliable correlation between ground vehicle friction measurements and aircraft braking performance."[5] NASA tested runway friction conditions using its Boeing 737 and an FAA-owned Boeing 727 at Langley, Wallops, the FAA Technical Center in New Jersey, and the Brunswick Naval Air Station in Maine between June 1983 and March 1986. Those tests showed that ground vehicle measurements correlated

Figure 9-4. Ames Research Center's FFC (Future Flight Central) Simulator interior with the "LAX" Configuration showing on the screens in 2002. NASA's Ken Christensen is in charge of the "tower." (NASA, ACD02-0050-2)

very well with aircraft performance and that grooved runways performed almost as well as dry runways in slippery and wet conditions. As a result, by the end of the 20th century, pavement was constructed using grooved surfaces on more than 1,000 commercial runways around the world. The results increased sixfold the friction measurements on those runways.

Likewise, NASA research into wind shear and the creation of an aircraft warning system resulted from an August 1986 crash of a Delta L-1011 at the Dallas/Ft. Worth Airport due to a violent weather system. Out of 163 passengers, 137 died as a radical downdraft caught the plane as it came in for a landing. This had been a longstanding problem for aircraft; "between 1964 and 1985, over 25 U.S. airline accidents, 625 fatalities, and 200 injuries were caused by wind shear."[6]

The public outcry led to the creation of the National Integrated Wind Shear Plan (1986), managed by the FAA, in which NASA undertook the development of an airborne detection system. Using a series of radars coupled with control systems during the summers of 1991 and 1992, NASA's Boeing 737 airborne laboratory tested concepts whereby Doppler and other radars could be used to detect microbursts early enough to allow pilots to act. This was quickly adopted as the industry standard.

Finally, NASA's efforts to enhance airway safety and efficiency also has a long history. NASA, and the NACA beforehand, had a role in almost every technological system developed to make the skyways better. As only one recent instance, beginning in the 1990s NASA Ames Research Center worked with the FAA to design new aeronautical air traffic and flight systems and to test new concepts. Using a simulator, FutureFlight Central, NASA tested an air traffic control tower in real-life situations. With large screens all around, control panels underneath may be used to approximate conditions in a real control tower at an actual airport. The findings coming out of research at FutureFlight Central have been incorporated into the current air traffic control system.

Collectively, these activities have transfigured the skyways.

CHAPTER 10

Toward a Permanent Human Presence in Space

"We ain't gonna do it with the tools we got," announced astronaut Pete Conrad during the extravehicular activity (EVA) to rescue Skylab on 25 May 1973.[1] His crewmate, Paul Weitz, stood in the hatch of the Apollo capsule as he hooked and pulled on the array while Joe Kerwin held his legs. Conrad tried to hold the Apollo spacecraft steady because Weitz's efforts pulled it toward the Skylab workshop. Weitz then replaced the hook with a universal prying tool when the array did not budge, but to no avail. Their efforts thwarted, the astronauts docked with Skylab and closed out a 22-hour day. The crew then deployed a solar shield parasol through a small scientific airlock with the intent of shading the spacecraft from solar heat.

Conrad's Skylab crew had to wait to try deploying that solar array again. A team on the ground led by astronaut Rusty Schweickart developed an EVA solar array repair procedure. The astronauts, in space, fabricated tools from on-board materials to carry out this repair, assembling six 5-foot rods with a cable cutter attached to the end, and then tied 20 feet of rope to pull the cutter. This permitted the astronauts to operate the cutter from afar. Using this tool, astronauts Conrad and Kerwin freed the jammed solar array and increased power to the workshop during a crucial EVA of 3 hours and 25 minutes. Deploying the array had not been an easy task, however. As Conrad later said: "I was facing away from it, heaving with all my might, and Joe was also heaving with all his might when it let go and both of us took off. By the time we got settled down…those panels were out as far as they were going to go."[2]

Skylab: A Preliminary Space Station

The Skylab rescue was an auspicious start for the Skylab orbital workshop, a tangible realization of NASA's space station dreams as well as an object lesson in how hard such dreams were to accomplish. Eventually, three crews visited Skylab in 1973 and 1974 and greatly extended knowledge of long-duration spaceflight. In the late 1960s, many in the leadership of the American space program realized that the abundant resources that had been made available for Project Apollo would not be offered for the proposed NASA space station. They advocated that the development of a permanent presence in space would open the door for a myriad of other space activities. This prompted the development of an orbital workshop leading to a space station, which fundamentally affected the course of space exploration into the 21st century. Skylab was only the first of these endeavors, but it also included the current development and operation of the International Space Station.

Skylab, America's first experimental space station, originated in the 1960s to prove that humans could live and work in space for extended periods and to expand knowledge of solar astronomy beyond what could be achieved from Earth-based observations. It made extensive use of Saturn and Apollo equipment, an idea that had been germinating within NASA since 1963, by using a reconfigured and habitable third stage of the Saturn V rocket as the basic component of the orbital station.

The 100-ton orbital workshop was launched into orbit on 14 May 1973, the last use of the giant Saturn V launch vehicle. Almost immediately, technical problems developed due to vibrations during liftoff, causing the need for the dramatic spacewalks of Conrad, Kerwin, and Weitz. Sixty-three seconds after launch, the meteoroid shield—designed also to shade Skylab's workshop from the Sun's rays—ripped off, taking with it one of the spacecraft's two solar panels, and another piece wrapped around the other panel, thereby keeping it from properly deploying. NASA's Mission Control personnel maneuvered Skylab so that its Apollo Telescope Mount (ATM) solar panels faced the Sun to provide as much electricity as possible, but because of the loss of the meteoroid shield, this positioning caused workshop temperatures to rise to 126 degrees Fahrenheit.

Once the Apollo crew arrived, astronauts Pete Conrad, Paul Weitz, and Joe Kerwin turned Skylab into a habitable orbital workshop. By early 4 June, the workshop was in full operation, and the crew set about conducting solar astronomy and Earth resources experiments, medical studies, and five student experiments. This crew made 404 orbits and carried out experiments for 392 hours, in the process making 3 EVAs totaling 6 hours and 20 minutes. The first group of astronauts returned to Earth on 22 June 1973, and two other Skylab missions followed.

NASA was delighted with the scientific return from the Skylab program despite its early and reoccurring mechanical difficulties. A total of three

Figure 10-1. An overhead view of the Skylab orbital workshop as the last crew departs for Earth in 1974. (NASA, sl4-143-4706)

3-person crews occupied the Skylab workshop for a total of 171 days and 13 hours. It was the site of nearly 300 scientific and technical experiments. In Skylab, both the total hours in space and the total hours spent in the performance of EVA under microgravity conditions exceeded the combined totals of all of the world's previous spaceflights up to that time.

Following the final occupied phase of the Skylab mission, ground controllers performed some engineering tests of certain Skylab systems—tests that ground personnel were reluctant to do while astronauts were aboard—positioned Skylab into a stable attitude, and shut down its systems. It was expected that Skylab would remain in orbit 8 to 10 years, by which time NASA might be able to reactivate it. In the fall of 1977, however, Agency officials determined that Skylab had entered a rapidly decaying orbit—resulting from greater-than-predicted solar activity—and that it would reenter Earth's atmosphere within two years. They steered the orbital workshop as best they could so debris from reentry would fall over oceans and unpopulated areas of the planet. On 11 July 1979, Skylab finally impacted Earth's surface. The debris dispersion area stretched from the Southeastern Indian Ocean across a sparsely populated section of Western Australia.

NASA and the U.S. space program took criticism for this development, ranging from the sale of hardhats as "Skylab Survival Kits" to serious questions about the propriety of spaceflight altogether if people were likely to be killed by falling objects. In reality, while NASA took sufficient precautions so no one was injured, its leaders had learned that the Agency could never again allow a situation in which large chunks of orbital debris had a chance of reaching populated portions of Earth's surface.

Planning the Space Station

The idea of a space station did not die with Skylab. As soon as the Space Shuttle began flying in 1981, the space agency lobbied political leaders for approval of a space station as a location for science, materials processing, repair and refurbishment, and a jumping-off point for missions to the Moon and Mars. While the space station was never an entity unto itself, relying as it did upon the Shuttle to resupply it, the Space Shuttle was also envisioned as a critical component in reaching the station.

In a measure of political acumen not seen at NASA previously, Agency Administrator James M. Beggs persuaded President Ronald Reagan, against the wishes of many presidential advisors, to endorse the building of a permanently occupied space station. Beggs deserves recognition for his circumvention of opposition from Caspar Weinberger and other leaders in the Reagan administration to persuade the President to support the space station. In a "Kennedyesque" moment in January 1984, Reagan declared that "America has always been greatest when we dared to be great. We can reach for greatness again. We can follow our dreams to distant stars, living and working in space for peaceful, economic, and scientific gain. Tonight I am directing NASA to develop a permanently manned space station and to do it within a decade."[3]

In 1985, the space agency came forward with designs for an $8 billion dual-keel space station configuration, to which were attached a large solar power plant and several modules for microgravity experimentation, life science, technical activities, and habitation. This station also had the capacity for significant expansion through the addition of other modules.

From the outset, both the Reagan administration and NASA intended Space Station Freedom, as it was then called, to be an international program. Although a range of international cooperative activities had been carried out in the past—Spacelab, the Apollo-Soyuz Test Project, and scientific data exchange—the station offered an opportunity for a truly integrated effort. The inclusion of international partners, many now with their own rapidly developing spaceflight capabilities, could enhance the effort. In addition, every partnership brought greater legitimacy to the overall program and might help to insulate it from drastic budgetary and political changes. Inciting an international incident because of a change to the station was something neither U.S. diplomats nor politicians relished. That fact, it was thought, could help stabilize funding, schedule, or other factors that might otherwise be changed in response to short-term political needs.

NASA leaders understood these positive factors but recognized that international partners would also dilute their authority to execute the program as they saw fit. Throughout its history, the space agency had never been very willing to deal with partners, either domestic or international, as coequals. It had tended to see them more as a hindrance than help, especially when they might get in the way of the "critical path" toward any technological goal. Assigning an essentially equal partner responsibility for the development of a critical subsystem meant giving up the power to make changes, to dictate solutions, to control schedules, and other factors. Partnership, furthermore, was not a synonym for contractor management, something Agency leaders understood very well, and NASA was not very accepting of full partners unless they were essentially silent or at least deferential. Such an attitude militated against significant international cooperation.

In addition to this concern, some technologists expressed fear that bringing Europeans into the project really meant giving foreign nations technical knowledge that only the United States held. No other nation could build a space station on a par with Freedom, and only a handful had a genuine launch capability. So many government officials questioned the advisability of reducing America's technological lead. The control of technology transfer in the international arena was an especially important issue to be considered.

In spite of these concerns, NASA leaders pressed forward with international agreements among 13 nations to take part in the Space Station Freedom program. Japan, Canada, and the nations pooling their resources in the European Space Agency (ESA) agreed in the spring of 1985 to participate. Canada, for instance, decided to build a remote servicing system. Building on its Spacelab experience, ESA agreed to build an attached pressurized science module and an astronaut-tended free-flyer. Japan's contribution was the development and

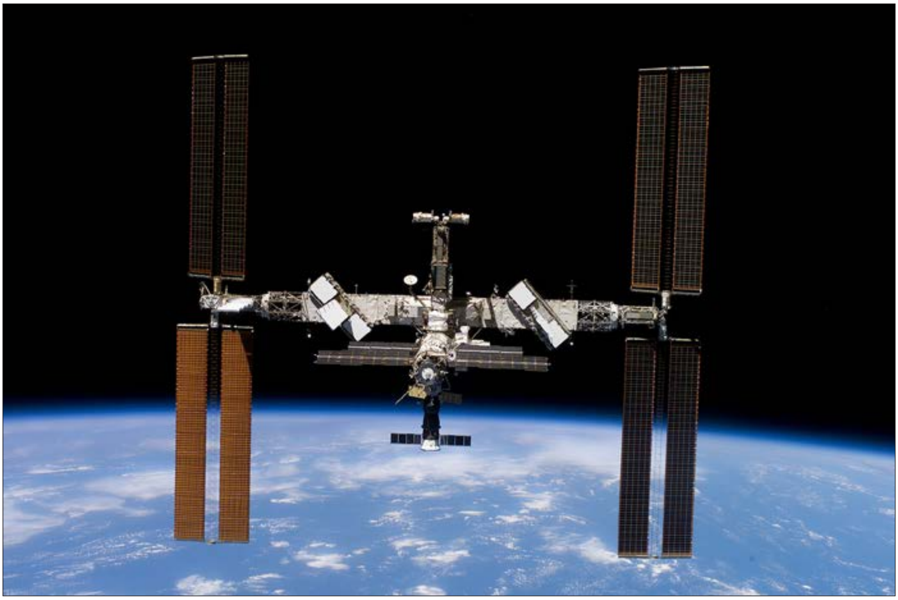

Figure 10-2. During mission STS-117, Space Shuttle Atlantis leaves the International Space Station in 2007. (NASA, s117e08056)

commercial use of an experiment module for materials processing, life sciences, and technological development. These separate components, with their "plug-in" capacity, eased somewhat the overall management (and congressional) concerns about unwanted technology transfer.

Almost from the outset, the Space Station Freedom program was controversial. Most of the debate centered on its costs versus its benefits. One NASA official remembered that "I reached the scream level at about $9 billion," referring to how much U.S. politicians appeared willing to spend on the station.[4] As a result, NASA designed the project to fit an $8 billion research and development funding profile. For many reasons, some of them associated with tough Washington politics, within five years the projected costs had more than tripled and the station had become too expensive to fund fully in an environment in which the national debt had exploded in the 1980s.

NASA pared down the station budget, in the process eliminating functions that some of its constituencies wanted. This led to a rebellion among some former supporters. For instance, the space science community began complaining that the space station configuration under development did not provide sufficient experimental opportunity. Thomas M. Donahue, an atmospheric scientist from the University of Michigan and chair of the National Academy of Sciences' Space Science Board, commented in the mid-1980s that his group "sees no scientific need for this space station during the next twenty years." He also suggested that "if the decision to build a space station is political and social, we have no problem with that" alluding to the thousands of jobs associated with it. "But don't call it a scientific program."[5]

Redesigns of Space Station Freedom followed between 1990 and 1993. Each time, the project got smaller, less capable of accomplishing the broad projects originally envisioned for it, less costly, and more controversial. As costs were reduced, capabilities also had to diminish, and increasingly political leaders who had once supported the program questioned its viability. It was a seemingly endless circle, and political wits wondered when the dog would wise up and stop chasing its tail. Some leaders suggested that the nation, NASA, and the overall space exploration effort would be better off if the space station program were terminated. Then, after a few years had passed and additional study and planning had been completed, NASA could come forward with a more viable effort.

Congress did not terminate the program in part because of the desperate economic situation in the aerospace industry—a result of an overall recession and of military demobilization after the collapse of the Soviet Union and the end of the Cold War—and the fact that by 1992 the project had spawned an estimated 75,000 jobs in 39 states, most of which were key political battleground states such as California, Florida, Texas, and Maryland. Politicians were hesitant to kill the station outright because of these jobs, but neither were they willing to fund it at the level required to make it a truly viable program. Barbara Mikulski (D-MD), chair of the Senate Appropriations subcommittee that handled NASA's budget, summarized this position: "I truly believe that in space station Freedom we are going to generate jobs today and jobs tomorrow—jobs today in terms of the actual manufacturing of space station Freedom, but jobs tomorrow because of what we will learn."[6]

In the latter 1980s and early 1990s, a parade of space station managers and NASA Administrators, each of them honest in their attempts to rescue the program, wrestled with Freedom and lost. They faced on one side politicians who demanded that the jobs aspect of the project—itself a major cause of the overall cost growth—be maintained, and with station users on the other side demanding that Freedom's capabilities be maintained, and with people on all sides demanding that costs be reduced. The incompatibility of these various demands ensured that station program management was a task not without difficulties. The NASA Administrator beginning 1 April 1992, Daniel S. Goldin, was faced with a uniquely frustrating situation when these competing claims were made official by the new President, William J. Clinton, who told him in the spring of 1993 to restructure the space station program by reducing its budget, maximizing its scientific use, and ensuring that aerospace industry jobs were not lost.

This was part of a larger agenda in Washington in the early 1990s to reduce NASA's funding and range of activities. NASA Administrator between 1992 and 2001, Daniel S. Goldin commented about meeting and talking with Senator Fritz Hollings (D-SC) during the confirmation process in spring 1992. Hollings drew him a graph that tracked over time the budget that NASA had requested, showing that it went up at a steady rate over the years. Hollings then drew for him the budget that Congress—and presumably the White House as well—envisioned for NASA. It was a flat line as far as the eye could see. The point was clear. NASA was not going to get an increase in its budget, despite its pressing for one and despite the recommendations of independent analyses calling for increases to the NASA appropriation.

Goldin also met with President Clinton and Office of Management and Budget head Leon Panetta only nine days after Clinton was sworn in as President in January 1993. Panetta drew essentially the same graph as Hollings, showing what NASA wanted and what the White House would be able to support. The attempt to hold the NASA budget flat throughout the 1990s, which played out in actuality throughout the Clinton administration, proved Hollings prophetic, as the budget remained essentially level.

This had a profound impact on all NASA efforts, but especially the construction of the space station. Told to come up with a plan that included both the Russians in the space station and a budget target that the President could support, NASA came forward with three redesign options for a space station; high, middle, and low options. On 17 June 1993, President Clinton decided to proceed with a moderately priced, moderately capable station design. Near the same time, the post–Cold War environment enabled NASA to negotiate a landmark decision to include Russia in the building of an international space station. On 7 November 1993, the United States and Russia announced they would work together with the other international partners to build a space station for the benefit of all. Even so, the multinational space station program remained a difficult issue as public policy-makers wrestled with competing political agendas. The political coalition has, however, remained in place thereafter. In this agreement, both sides gained much; the Russians maintained their program with an infusion of hard currency from NASA while ensuring their place as one of the two most successful space programs in the world and the Americans obtained a highly capable and reliable partner in the most difficult space activity undertaken since the Moon landings.

Building the ISS

After bringing the Russians into the International Space Station (ISS) program, NASA leaders pursued the development of modules and led the effort to assemble them in orbit. While there were enormous difficulties to overcome in the project—cost overruns, questions about the quality of science to be undertaken, the role of civilians who wanted to fly, even the need for the facility—one may appropriately conclude that the ISS effort was successful. This is true for three major reasons.

First, the fact that this station was built at all by a large international consortium is extraordinary, given the technical, financial, and political obstacles involved. The U.S. House of Representatives came within a single vote of canceling the entire effort in 1993. Space organizations from a multitude of nations have struggled to overcome cultural differences on this enormously complex high-technology undertaking. Second, the International Space Station provided the most sophisticated model ever offered for tax-financed human activities in space. One hundred years hence, humans may well look back on the building of the Station as the first truly international endeavor among peaceful nations. No question, it was the most sophisticated international effort ever attempted on the space frontier. Third, the Station helped to revitalize the spacefaring dream. Once functioning in space, the Station energized the development of private orbital laboratories and other capabilities that turned low-Earth orbit into a normal realm of human activity. The ISS has permitted research not possible on Earth in such areas as materials science, fluid physics, combustion science, and biotechnology.

Costing all of the Space Station partners some $100 billion in the aggregate over its construction and operation to 2020, the ISS always had schedule and cost difficulties. As an independent blue ribbon investigation on ISS Cost Assessment and Validation under Jay Chabrow concluded in 1998, "NASA's schedule and cost commitments were definitely success-oriented, especially considering the new realigned contracting approach with a single Prime contractor and that the specifics of Russia's involvement were just being definitized."[7] In other words, NASA over-promised what it could deliver for the money expended and the schedule agreed upon.

Beyond the American commitment to building the lion's share of the Station, NASA successfully led its international partners—Canada, Japan, the European Space Agency, and Russia—to contribute the following key elements to the International Space Station:

- Canada provided a 55-foot-long robotic arm to be used for assembly and maintenance tasks on the Space Station.

- The European Space Agency built a pressurized laboratory launched on the Space Shuttle and logistics transport vehicles launched on the Ariane 5 launch vehicle.
- Japan built a laboratory with an attached exposed exterior platform for experiments as well as logistics transport vehicles.
- Russia provided two research modules, an early living quarters called the Service Module with its own life support and habitation systems, a science power platform of solar arrays that can supply about 20 kilowatts of electrical power, logistics transport vehicles, and Soyuz spacecraft for crew return and transfer.[8]

Later, Brazil and Italy agreed to enter the partnership and contribute some equipment to the Station through agreements with the United States.

Difficulties abounded as modules for the ISS were under construction; many of them relating to cost. When the Freedom program became the International Space Station, NASA believed it could build the Station on a budget of $17.4 billion over a 10-year period. It could not have been more wrong had it set out to offer disinformation. After three years of insisting that it could build the ISS for $17.4 billion, in September 1997 NASA finally conceded it would need an additional $430 million in FY 1998 to continue. NASA began transferring funds from other NASA programs into Space Station construction. By the time of a major review in the fall in 2001, the estimated U.S. portion of the ISS development stood at more than $23 billion.

Most troubling, NASA managers kept silent until after the 2000 presidential election about the fact that they knew a cost addition of $4 billion for U.S. work on the ISS was needed in fiscal years 2002 to 2006. By 2020, the total investment in the ISS was approximately $150 billion, of which the American portion approached $100 billion. During controversies over the ISS costs, NASA officials defended the program, saying that much of the U.S. hardware had already been built, and more was in the process of completion. And some had already been assembled on orbit and made operational. All of that represented sunk costs. Leaders at NASA argued that continuing the ISS construction was the only means of realizing any return on that investment. They made this case to the Bush and Obama administrations throughout the early 21st century, while also scrubbing everything of the ISS program that might help save some money. This proved successful, and barring a catastrophe the program was past its major cost hurdles.

Meantime, on-orbit construction of the ISS proceeded. The first two elements, a Russian module and an American node, were assembled by a Space Shuttle crew in December 1998. Flights followed periodically thereafter. At the

Figure 10-3. STS-88 mission specialist James Newman, holding on to a handrail, waves back at the camera during the first of three extravehicular activities (EVAs) performed during the mission in 1998. The orbiter can be seen reflected in his visor. (NASA, STS088-343-025)

beginning of the 21st century, the effort involved 16 nations, and through the ending of the Space Shuttle in 2011 concerted efforts took place to complete the ISS.

The Columbia accident of 1 February 2003, resulting in the deaths of seven astronauts, grounded the Space Shuttle fleet and thereby placed on hold construction of the ISS. Access to the Station, thereafter, came only through the use of the Russian Soyuz capsule, a reliable but limited vehicle whose technology extended back to the 1960s. Because of this limitation, the ISS crew was cut to two members in May 2003, a skeleton workforce designed to keep the Station operational.

When the Space Shuttle resumed operations in 2006, efforts to complete the ISS took a more aggressive turn. In all, between 1998 and 2011, NASA and the Russian Space Agency made 40 assembly flights for the ISS. Thirty-four of those assembly flights were completed by astronauts aboard Space Shuttle missions.

Science on the ISS

Soon after the launch of its first elements in 1998, the ISS began to offer scientists, engineers, and entrepreneurs an unprecedented platform on which to perform complex, long-duration, and replicable experiments in the unique environment of space. Research opportunities for the future involved prolonged exposure to microgravity, and the presence of human experimenters in the research process.

Scientific inquiry represented the fundamental activity taking place on the International Space Station. NASA has soft-pedaled the idea of using the ISS as a jumping-off point for future exploration of the Moon and planets, although that remains a long-term objective. Some advocates have emphasized the Station's significance as a laboratory for the physical sciences, with materials processing in microgravity the chief research. Still others suggest that human-factors research will gain a leap forward because of the work on the ISS, simply because data about changes to the bodies of astronauts engaging in long-duration spaceflight will expand the base of scientific knowledge. Finally, the ISS has offered a platform for greater scientific understanding of the universe, especially about the origins and evolution of the Sun and the planets of this solar system. Those four scientific endeavors—biotech research, materials science, human factors, and space science—represented broad scientific opportunities on the ISS.

Advocates of the Space Station have raised concerns about the lack of clarity of its science mission. Representative Ralph M. Hall (D-TX), speaking before a gathering of senior aerospace officials on 27 March 2001, commented that the space program was in "a time of transition" and that he and his colleagues in Congress had lost patience. He said, "after all of the taxpayer dollars that have been invested in the Space Station, we will need to ensure that we wind up with the world-class research facility that we have been promised."[9] As an aside to his prepared remarks, Representative Hall commented that once the ISS became operational, NASA had better find a way to use it effectively. He warned that some astounding scientific discovery should be forthcoming—a cure for cancer, specifically—or the program could fall by the wayside.

During the first two decades of the 21st century, the critical component for research on the Space Station became learning about how humans reacted to long-duration stays in a microgravity environment. ISS research has found that weightlessness affects almost every aspect of the human body, including the heart, lungs, muscle, bones, immune system, and nerves. Coining the term *bioastronautics* to cover this research agenda, NASA implemented beginning with the Expedition 3 crew a research program that sought to identify and characterize health, environmental, and other operational human biomedical risks associated with living in space. It also aimed to develop strategies, protocols, and technologies that might prevent or reduce those risks. Only by understanding exactly how the components of the human body change during weightlessness and how the human mind reacts to confinement and isolation can humanity ever hope to live in space and to journey to Mars.

Many of the physiological changes in astronauts actually resemble changes in the human body normally associated with aging. For instance, in addition to losing mass in the microgravity environment, bones and muscle do not appear to heal normally in space. By studying the changes in astronauts' bodies, research from the ISS has played a key role in developing a model for the consequences of aging in space and potential responses to it.

NASA's Destiny Laboratory Module became the centerpiece of ISS scientific research. It was launched aboard STS-98 on 7 February 2001, with 24 racks occupying 13 locations specially designed to support experiments. More than 1,000 experiments had been completed by the end of 2019, ranging from materials science to biology, but with emphasis on life sciences.

In addition, there have been other ways researchers have accessed the capabilities of the ISS. One of the most innovative was through Nanoracks, LLC. Nanoracks facilitates scientific research on the ISS by offering autonomous

Figure 10-4. The Nanoracks CubeSat Deployer in operation on the ISS, 4 August 2017. (NASA, nanorack_deployment.jpg)

Figure 10-5. One of the last pieces of hardware to be assembled on the International Space Station, this cupola provides a window on the world. Floating just below the ISS, astronaut Nicholas Patrick puts some finishing touches on the newly installed cupola space windows in 2010. (NASA, 429583main_installingcupola_nasa_big)

experiments packages that may be brought to the Station by resupply vehicles, loaded into experiment bays, and tended by astronauts, with the data automatically sent back to researchers on the ground. This has greatly expanded the capability for research in orbit; since 2009, this company has delivered more than 580 experiments to the ISS. A major innovation came on 9 January 2014, when the Orbital Sciences Cygnus Orb-1 mission launched the Nanoracks CubeSat Deployer, making possible the deployment of tiny cube-shaped mini-satellites from the ISS. Each CubeSat is laden with scientific instruments and usually measures around 4 in^3 (10 cm^3) in volume. Since that time, the ISS has become a major launch point for swarms of CubeSats with a wide variety of functions. Both the Nanoracks experiments packages and their CubeSat deployment capabilities on the ISS have enhanced the potential for science while also lowering its cost.

A Meaning for the Space Station

Does the science conducted on the ISS justify its enormous cost of development, construction, and operation? The answer depends very much on individual perspective. Generally speaking, space advocates argued for the ISS as a great boon to scientific knowledge, but in the larger community many questions remain as to whether or not the funds might have been more effectively applied to other equally or more valuable research projects. The *New York Times* editorialized: "in truth, it has never been clear just what science needs to be done on a permanently manned platform in space as opposed to an unmanned platform or an earthbound facility."[10] NASA's failure to define a clearly supportable science mission left some wits to suggest that the ISS was very much like the movie *Field of Dreams*, in the which the central character plows under his corn field to erect a baseball diamond in Iowa because a voice says, "If you build it, they will come."[11] Just because the ISS was in orbit, they noted, why would anyone think it a foregone conclusion that the science program offered genuine value?

One issue is significant regardless of the scientific knowledge gained through ISS research: it has helped to turn low-Earth orbit into a normal realm of human activity. The 1960s was the era of exploration in space; no one knew what we would find and especially what might result. The Space Shuttle and the Space Station, however, opened the region to much broader activity. Space, certainly orbital space, no longer presents unknown challenges. It now offers the opportunity for utilization, and the ISS facilitated this transformation.

CHAPTER 11

A New Age of Entrepreneurial Space Operations

In April 2010, Apollo astronauts Neil Armstrong (Apollo 11), Gene Cernan (Apollo 17), and Jim Lovell (Apollos 8 and 13) famously sent U.S. President Barack Obama a letter warning that failure to pursue aggressively a new space launch capability "destines our nation to become one of second- or even third-rate stature."[1] They were responding to the decision to terminate the Space Shuttle program in favor of a large new human launch system, Project Constellation, upon the completion of the International Space Station (ISS) that was then on the chopping block in the aftermath of the "Great Recession" of 2008–10. Instead of smoothly transitioning from one NASA human launch vehicle, the Space Shuttle, to another, Constellation, cost overruns on the new spacecraft prompted the recently installed Obama administration to question the necessity of the whole thing.

It was a morass of the first magnitude; the fortunes of human spaceflight in the United States had not been at such a nadir since the 1970s. NASA had forestalled any serious discussion of the propriety of human space exploration with the reusable Space Shuttle in that decade, and through 30 years of operation it had maintained that capability. It might not have been as glamorous as the earlier heroic human space efforts, but it was a workhorse that performed a succession of useful missions over the years, but always at a high cost.

In the aftermath of the Columbia Shuttle accident on 1 February 2003, however, President George W. Bush decided that the Space Shuttle Program had served its purpose and announced a decision to retire the entire fleet near the end of the first decade of the 21st century. Speaking at NASA Headquarters on 28 January 2004, Bush proposed a "Vision for Space Exploration" that mandated NASA's development of what became known as the Constellation program that would yield a new human spaceflight vehicle that could extend exploration beyond low-Earth orbit. NASA acted on that decision by working hard to complete the ISS, which required Space Shuttle support, and formally terminating the program with the 135th flight on 8–21 July 2011.

Meantime, early in the administration of President Obama in 2009, space policy turned in a direction just as strikingly different as what had taken place in the transition from Apollo to the Space Shuttle in the early 1970s. The new President convened a blue-ribbon panel chaired by Norm Augustine, the former CEO of Lockheed Martin and a longstanding space guru, that recommended in the fall of that year harnessing private-sector, especially entrepreneurial, firms in supporting Earth orbital operations instead of relying on a NASA program that was behind schedule and over budget. Time was of the essence; the Space Shuttle was to be retired by 2011, a decision made in 2004 by President George W. Bush, and the Constellation Program intended to replace NASA's heavy lift capability and make possible a return to the Moon was over budget, behind schedule, and underperforming as a launch technology.. This unleashed a broad-based entrepreneurial effort that has yet to be fully resolved but holds great promise in NASA relying on commercial firms for support for its Earth orbital activities. Already, companies such as SpaceX and Northrop Grumman, which acquired Orbital Sciences, are providing resupply services for the ISS. SpaceX also began crew rotation missions to the ISS in 2020.

Beginning Commercial Activities in Space

While much of the history of the Space Age is dominated by national actors, there has been almost from the beginning a significant private-sector involvement as well. The first commercial activities in space resulted from the initiatives of the telecommunications industry to extend operations beyond the atmosphere almost with the beginning of the Space Age. Indeed, satellite communication was the only truly commercial space technology to be developed in the first decade or so after Sputnik. The first active-repeater telecommunications satellite, Telstar, flew in 1962, and since that time the industry has expanded into a multibillion-dollar business each year. So have commercial remote sensing, navigation, and other initiatives thereafter.

With the arrival of the Reagan administration in 1981, efforts to expand commercial activities in space became a much higher priority. The President's National Space Policy of 4 July 1982 took a significant step when it directed NASA to expand U.S. private-sector investment and involvement in space-related activities. Accordingly, NASA undertook an in-depth review detailing options NASA might undertake that could stimulate commercial investments and opportunities. Advocates argued for a new way of thinking at NASA; as the review team noted, the Agency needed to consider commercial ventures rather than R&D for itself. It explicitly called for NASA to "more effectively encourage and facilitate private sector involvement and investment in civil space and space-related activities."[2] It also emphasized the development of cost-sharing arrangements with NASA conducting R&D and the private sector undertaking operational activities.

In the last year of the Reagan administration, the Presidential Directive on National Space Policy offered for the first time a major section on commercial space efforts, reflecting positive commercial efforts in the communications satellite and launch vehicle sectors. It prohibited NASA from operating an expendable launch vehicle program and encouraged the government to purchase commercial launch services. It also called for open private space activities in microgravity, remote sensing, and other space ventures where there was potential for commerce. The George H. W. Bush administration issued its Commercial Space Policy Guidelines in 1991 that expanded on some of these same themes and emphasized the stimulation of private investment in launch, satellite, and support activities. The Guidelines explicitly recognized the use of space for commercial purposes and directed government agencies to procure every space technology available on the open market from private firms. It also mandated that NASA and other agencies using space avoid practices that might be viewed as deterring commercial space activities.

The Clinton administration's 1996 Presidential Space Directive pushed these practices even further into the mainstream of national economic policy and international competitiveness. It explicitly stated: "To stimulate private sector investment, ownership, and operation of space assets, the U.S. Government will facilitate stable and predictable U.S. commercial sector access to appropriate U.S. Government space-related hardware, facilities and data."[3] A continuation and extension of earlier policies going back to the Reagan administration, this directive was also the first to specifically detail the process by which the government might stimulate economic and business activity from space programs. It reflected the end of the Cold War, the shrinking federal discretionary budget, the maturity of some parts of the space program, and international competitive pressures.

Collectively, this policy milieu stimulated some investment in such arenas as space launch and satellite development and operation. Communications satellites led the parade of investment—especially Iridium Satellite LLC, Globalstar, and DirecTV—but remote sensing, navigation, and other applications satellite systems followed. Such launcher manufacturers, especially Orbital Sciences in the 1980s, emerged to challenge traditional Delta, Atlas, and Titan launch vehicles. While many firms worked to build new launch systems, the only truly successful one to come out of this period of ferment was Orbital Sciences.

Figure 11-1. The Pegasus launcher was first developed by Orbital Sciences Corp. as a commercial launcher in the 1980s and had a lengthy career as an air-launched rocket delivering payloads to Earth orbit. Here NASA's B-52 mother ship takes off with the second Pegasus vehicle under its wing from the Dryden Flight Research Facility in July 1991. (NASA, 330365main_EC91-348-3_full)

The company's approach was unique, with an air-launched Pegasus rocket flown off of a Lockheed L-1011. Carrying the three-stage solid-fuel rocket to its launch altitude of 39,000 feet, the L-1011 then released Pegasus for a free-fall for 5 seconds until the first-stage rocket motor ignited, followed by the other stages. Pegasus was designed as a low-cost vehicle for launching lightweight satellites—1,000 pounds or less. Air-launching the vehicle meant that the operator could dispense with expensive ground facilities, elaborate launch preparations, and numerous personnel. It was also typically launched over the ocean, away from population centers. The brainchild of Antonio L. Elias, Pegasus first flew on 5 April 1990, and since that first flight, Pegasus has launched 44 times and placed in orbit more than 100 satellites. NASA has purchased launch services from Orbital Sciences several times since it began orbital operations.

The First Space "Gold Rush"

Beginning in the mid-1990s, several entrepreneurs organized start-up companies to develop new vehicles in response to an envisioned expansive market for space access. Indeed, 1996 marked something of a milestone in this history. In that year, worldwide commercial revenues in space for the first time surpassed all governmental spending on space, totaling some $77 billion. This growth continued in 1997, with 75 commercial payloads lofted into orbit, and with approximately 75 more military and scientific satellites launched. This represented a threefold increase over the number the year before. Market surveys for the period thereafter suggested that commercial launches would multiply for the next several years at least: one estimate holding that 1,200 telecommunications satellites would be launched between 1998 and 2007. In that context, many space launch advocates believed that the market had matured sufficiently that government investment in launch vehicle development was no longer necessary. Instead, they asked that the federal government simply "get out of the way" and allow the private sector to pursue development free from bureaucratic controls.

This modern "Gold Rush" sparked several new corporations to muscle their way into the tight conglomerate of launch vehicle companies. One of the farthest along and best financed of this new breed was Kistler Aerospace Corporation, based in Kirkland, Washington. Seeking low-cost access to space, Kistler employed Russian-built engines as a centerpiece of its K-1 reusable launcher. It was intended to deliver up to 10,000 pounds to orbit, depending on inclination. The first stage of this vehicle would fly back to the launch site; the second would orbit Earth before returning. Both stages would descend by parachute and land on inflatable air bags. Pioneer, Inc., also emerged, championing the Pathfinder spaceplane that could accommodate a crew of two and deliver a payload of 5,000 pounds to orbit. Kelly Space and Technology, Inc., worked on its Astroliner, a reusable spaceplane that could deliver 11,000 pounds to low-Earth orbit for a cost of $2,000 per pound. Among these companies, the most interesting concept was Roton by the Rotary Rocket Company. Roton was intended as a fully reusable, single-stage-to-orbit (SSTO) space vehicle with a helicopter landing system designed to transport up to 7,000 pounds to and from space. Roton sought to enter commercial service in the year 2000 with a target price per flight of $7 million ($1,000 per pound).

Other space launch firms experimented with unique launch approaches. The Sea Launch Company LLC used a floating mobile platform that could handle launches of heavy vehicles out of its Long Beach, California, facilities. This launch method reduced legal, operational, and infrastructure costs. Since it was mobile it offered equatorial launches in any inclination from a single launch pad, providing maximum efficiency from the launcher. Established as a partnership between Boeing (U.S.), Aker ASA (Norway), RSC-Energia (Russia), and SDO Yuzhnoye/PO Yuzhmash (Ukraine), the Sea Launch Company was organized on 3 April 1995. It then constructed its platform and launched its first test payload into orbit on 27 March 1999. Using a jointly produced Zenit-3SL launcher built in the Ukraine and Russia, it flew its first commercial payload on 9 October 1999, a DIRECTV 1-R communications satellite. Since that time, Sea Launch has lifted more than 40 satellites into orbit. This system has been touted as a major success story in international commercial cooperation for space access.

Despite some other successes, only Orbital Sciences became viable over the long term. With the failure of the Iridium Corporation in spring 2000, a satellite communications system that many believed would be in the vanguard of business for a rapidly expanding commercial space launch market, investment for space enterprises became even scarcer. In some measure because of this, although they had previously eschewed government investment and the corresponding red tape, many of these start-ups began seeking capital from NASA and the military to support their efforts. Accordingly, it seemed that as the 21st century began, there was still a pressing need for substantial government investment in space launch R&D.

NASA and the X-33 Interlude

Private-sector efforts to develop new space launch systems, NASA's involvement in fostering them, and their limited success prompted Agency leaders to undertake a full-fledged public-private partnership in the mid-1990s to develop technology that had the potential to move beyond the Space Shuttle for space access. NASA and Lockheed Martin instituted a cooperative agreement to develop the X-33 experimental spaceplane in 1995, known also as the Advanced Technology Demonstrator Program. It had an ambitious timetable to fly by 2001. NASA initially invested approximately $1 billion while Lockheed contributed approximately half that amount.

Once the X-33 technology reached some maturity, Lockheed vowed to scale up the X-33 into a human-rated vehicle, VentureStar, which could serve as the Space Shuttle's replacement. As it turned out, the program was far more challenging both technologically and politically than originally envisioned. Among the technologies it would demonstrate were reusable composite cryogenic tanks, graphite composite primary structures, metallic thermal protection materials, reusable propulsion systems, autonomous flight control, and electronics and avionics.

Given the problems experienced on the X-33 program, with delays of more than a year because of difficulties with critical technical elements such as composite fuel tanks, NASA terminated the program in 2001. The NASA–Lockheed Martin partnership was pathbreaking in a fundamental way: before the X-33,

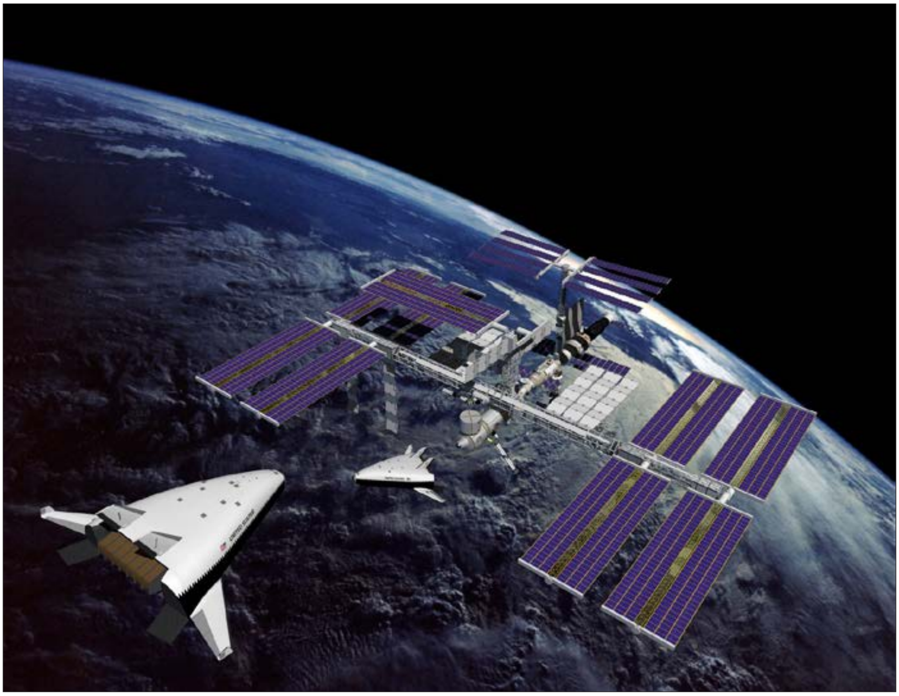

Figure 11-2. NASA had high hopes for the public-private partnership with Lockheed to build the X-33 technical demonstrator. This artist's concept depicts the X-33 en route to the International Space Station. (NASA, MSFC-9906375)

the space industry had rarely expended significant resources in launcher development. The industry contribution to X-33 development amounted to $442 million through 2000. In an era of declining government space R&D budgets, the importance of that investment cannot be underestimated, and it seems obvious that although a sizable government role in the development of future launchers will be required, this program proved that there was ample reason to pursue additional cooperative projects.

Of course, one may also legitimately condemn the overall X-33 effort as a self-deception that a single government program—even one using a new type of partnership relationship with industry—would prove able to solve the problems of space access. In this case, an ambitious program was created, hyped as the panacea for all space access challenges, underfunded, and then ridiculed when it failed. Unrealistic goals, coupled with impossible political demands, left the X-33 program stunned and stunted at century's end. As space policy analyst Scott Pace concluded, "it continued to blur the line, which should be bright, between revolutionary, high-risk, high-payoff R&D efforts and low-risk, marginal payoff evolutionary efforts to improve systems."[4]

More important, the X-33 program was an early object lesson in NASA's efforts to initiate so-called "new ways of doing business." It used expeditious acquisition procedures, streamlined bureaucracy, limited oversight, and allowed less investment by NASA. Industry became more of a partner than a contractor in this effort, an enormously important lesson for future human spaceflight initiatives in the 21st century. It paved the way for the partnerships between NASA and SpaceX, and other corporations, that enabled the replacement of the Space Shuttle as an American human launch vehicle.

Space Tourism

Just as significant as the X-33 in offering a model for a new path for NASA's R&D, space tourism forced NASA to rethink its American monopoly on humans in space. In the latter 1990s, several space entrepreneurs led by Peter Diamondis founded the X-Prize Foundation to stimulate innovation in space technology. In 1997, the foundation announced the Ansari X-Prize for the first privately developed and operated piloted craft to reach space twice within a one-week period. SpaceShipOne gained fame for winning this $10 million prize in 2004. It was a joint venture by legendary aircraft designer Burt Rutan and investor-philanthropist Paul G. Allen, cofounder of Microsoft. Rutan had for years been viewed as an innovative, and perhaps a little mad, designer of winged vehicles. He intended with SpaceShipOne to prove the concept of safe space tourism. The craft had distinctive swept wings with tail fins to accomplish a three-part flight profile. First, "White Knight" would carry the vehicle to 50,000 feet for launch. Second, a hybrid rocket motor—burning solid rubber with liquid nitrous oxide—powered SpaceShipOne to Mach 3. The vehicle then coasted to an altitude of more than 62 miles (100 kilometers) for a suborbital arc through space. As the craft returned to Earth, the pilot reconfigured the wing for reentry, landing like an aircraft on a runway. Pilot Mike Melvill took SpaceShipOne to 62 miles on 21 June 2004, and to 64 miles on 29 September. Brian Binnie flew it to 70 miles on 4 October 2004, thus claiming the X-Prize, endowed by Anousheh Ansari.

At the same time of SpaceShipOne's success, Sir Richard Branson, head of the Virgin Atlantic corporate empire, announced in front of the Royal Aeronautical Society in London on 27 September 2004 the establishment of Virgin Galactic LLC as the culmination of a 6-year-long plan to enter the space tourism business. Like the X-Planes that explored ever higher and faster frontiers during the 1950s and 1960s, the Virgin SpaceShipTwo passenger vehicle would be carried to high altitude by a carrier aircraft and then launched for a quick ballistic flight above 62 miles (100 kilometers). As Virgin Galactic officials pointed out about the experience, “It will be humbling. It will be spiritual.”[5] The first flights were projected to cost $200,000 and were planned to begin in 2008. While test flights of the spaceplane have taken place, and there has been one crash, Virgin Galactic’s VSS Unity completed a successful test flight with four passengers on 11 July 2021. Additionally, Blue Origin, the company of Amazon.com founder Jeff Bezos, developed the New Shepard reusable suborbital launch system for space tourism and sent four passengers to an altitude of 107 km (66 mi) on 20 July 2021.

Ironically, it was the former Soviet Union that led the way to commercial space tourism in 2001, when it aided an American billionaire to reach the ISS. In a flight that cost him a purported $20 million, a New York–born California investment manager and former aerospace engineer named Dennis Tito flew on a Russian spacecraft on 28 April 2001, spending eight days aboard the ISS in orbit. Without question, Dennis Tito deserves credit for kickstarting space tourism. Other billionaire tourists have followed since that time.

NASA came to this prospect reluctantly but later embraced the idea. Dennis Tito’s saga began in June 2000 when he signed a deal with MirCorp to fly aboard a Soyuz rocket to the Russian space station Mir. However, MirCorp went bankrupt and the Russians deorbited Mir before his flight, but Tito persisted in getting a seat on Soyuz TM-32 flying to the ISS. When NASA learned of this, its leaders refused approval for Tito’s flight. Tito gained notoriety for defying NASA, coalescing supporters as a cause célèbre among space activists. NASA eventually gave in to Tito’s demands, in the process learning that the period of the Agency’s suzerainty over space activities had ended. Partners had a say in decision-making, and new actors had to be negotiated with rather than dictated to. NASA was better for having learned this lesson.

Beyond the Space Shuttle

The issues associated with space entrepreneurship, private-sector investment, and greater public-private partnership in space activities gained a larger place in NASA history on 1 February 2003, with the loss of the Space Shuttle Columbia and the recommendation to replace the Space Shuttle with another human launcher. President George W. Bush announced a “Vision for Space Exploration” in January 2004 challenging NASA to complete the International Space Station, retire the Space Shuttle, and then move beyond low-Earth orbit.

What NASA came up with in response to Bush’s direction was the Constellation program, a presumed reuse of as much of the existing Space Shuttle technology as possible to build a new Ares I crew launch vehicle, consisting of a modified Space Shuttle solid rocket booster as a first stage and an

Figure 11-3. Following NASA's competition to stimulate private-sector investment in ISS support operations, SpaceX's Falcon 9 rocket and Dragon spacecraft undertake a test flight to the International Space Station on 8 December 2010. (NASA, 504364main_2010-5793_full)

external tank as the beginning point for a second stage. A new human space capsule, Orion, was to sit atop that system. A proposed second rocket, the Ares V cargo launch vehicle, would provide the heavy lift capability necessary to journey back to the Moon or to go beyond. Ares I was intended to carry a crew of up to six astronauts to low-Earth orbit in the Orion spacecraft, with the capability for expanding its use to send four astronauts to the Moon. Ares V was intended to serve as the Agency's primary vehicle for the delivery of large-scale hardware and cargo supporting an expansive space exploration agenda.

Such was not the case when the Constellation program was ended by the Barack Obama administration because of cost and technical challenges in 2010. Norm Augustine led a committee to develop options for Obama. "Under current conditions," its report stated, "the gap in U.S. ability to launch astronauts into space will stretch to at least seven years. The Committee did not identify any credible approach employing new capabilities that could shorten the gap to less than six years."[6] This would be true even with increased funding for NASA's program.

The panel also noted that a $3 billion a year increase for fiscal years 2010 through 2014 could return Constellation to health, a total of $15 billion altogether. As a measure of the low priority this effort enjoyed, there was no apparent enthusiasm for this type of expansion of the NASA budget. It was never considered as a serious solution to the Constellation program's misfortunes on either side of the political aisle. Some might suggest that this was because of a national debate on deficits then taking place, since the deficit was ballooning exponentially at the time by more than $1.5 trillion, and everyone was looking for places to reduce the size of government. Others might conclude differently, as I do, that with the national debt out of control, what is an additional $15 billion in the overall scheme of things? Regardless, national leaders did not rescue the Constellation program.

Instead, they seized on another recommendation of the Augustine panel: scrap Constellation, save the dollars, and try to leverage commercial interest in space access. "As we move from the complex, reusable Shuttle back to a simpler, smaller capsule, it is appropriate to consider turning this transport service over to the commercial sector," the panel concluded. "This approach is not without technical and programmatic risks, but it creates the possibility of lower operating costs for the system and potentially accelerates the availability of U.S. access to low-Earth orbit by about a year, to 2016. If this option is chosen, the Committee suggests establishing a new competition for this service, in which both large and small companies could participate."[7]

The response to this report from the space community was immediate. Some administration officials urged the President to cancel Constellation; others rallied to its defense. Edward Crawley, an MIT professor and a member of the Augustine panel, remarked that Ares I was suffering from technical issues that could only be overcome with more money and time. "It was a wise choice at the time," said Crawley, when asked about originating the program in 2005. "But times have changed…the budgetary environment is much tighter, and the understanding of the cost and schedule to develop the Ares I has matured."[8]

Based on these responses, President Obama proposed on 1 February 2010 (with more details added in a presidential speech on 15 April) a new path for future U.S. human spaceflight efforts. Central to this would be the termination of Constellation as a single entity; continuation of certain technology developments, such as the Orion space capsule; renewed commitment to operations on the International Space Station until at least 2020; and the fostering of private-sector solutions to human spaceflight operations in low-Earth orbit (LEO).

Proponents of this new strategy, among them Apollo 11 astronaut Buzz Aldrin, argued that the President's approach would return NASA to its roots as a research and development organization while private firms operated space systems. Turning orbital operations over to commercial entities could then empower NASA to focus on deep space exploration, perhaps eventually sending humans to the Moon again and on to Mars.

A debate ensued, one that was largely over maintaining a traditional approach to human spaceflight with NASA dominating the effort, owning the vehicles, and operating them through contractors. That was the method whereby America went to the Moon; it had proven successful over 50 years of human space exploration. Then there were those from the "new space" world that emphasized allowing private-sector firms to seize the initiative and pursue entrepreneurial approaches to human spaceflight. Advocates of the more traditional approach believed that the other side might sacrifice safety; advocates of the entrepreneurial approach criticized the forces of tradition by pointing out their large, over-budget, under-achieving space efforts.

While these concerns have been ever-present in the current debate over the future of human transportation into space in the United States, the primacy of commercial activities in this arena won the day. A decade later, NASA is on the verge of realizing its efforts to move beyond the Space Shuttle with new human spaceflight vehicles owned and operated by private-sector firms. In 2020, SpaceX, with its Falcon 9 launcher/Dragon capsule combination, began human flights to and from the ISS. This represented a major step toward operations for NASA's astronauts flying from Kennedy Space Center rather than Baikonur, Kazakhstan.

Getting to that point has been a long process, and several setbacks hindered development. First, because of the directive from the Obama administration privileging commercial solutions for space access, NASA began a multiphase space technology development program known as Commercial Crew Development (CCDev), inaugurated in 2010. Intended to stimulate development of privately operated crew vehicles to send to orbit, it awarded five firms—SpaceX, Orbital Sciences, Boeing, Paragon, and Sierra Nevada—$365 million in two rounds of funding to support their efforts to build new launch vehicles and crew capsules. As announced by Ed Mango, NASA's Commercial Crew Program manager: "The next American-flagged vehicle to carry our astronauts into space is going to be a U.S. commercial provider. The partnerships NASA is forming with industry will support the development of multiple American systems capable of providing future access to low-Earth orbit."[9]

In a follow-on competition, the Commercial Crew Integrated Capability (CCiCP), NASA also awarded in 2012 $1.167 billion to Boeing, SpaceX, and Sierra Nevada (with its Dream Chaser spaceplane for commercial crew support to the ISS). Once the capability matured, it was expected to be available both to the government and to other customers. In September 2014 NASA undertook a "downselect" to support Boeing and SpaceX human spaceflight programs, omitting Sierra Nevada from the award. Regardless, Sierra Nevada insisted it would continue spaceplane development on its own, and it has,

Figure 11-4. A second resupply rocket emerging from NASA's competition to stimulate private-sector investment to support the ISS was the Orbital Sciences Antares launcher, with the Cygnus cargo spacecraft aboard. This launch took place on 18 September 2013, from NASA Wallops Flight Facility, Virginia. (NASA, 201309180012hq_0)

although it now emphasizes cargo launch and recovery over human operations. In the third decade of the 21st century, NASA now possesses multiple options for both cargo and human access to the International Space Station with commercial firms.

Commercial Support of the ISS

The first capability to achieve reality with NASA's commercial partnerships relating to space access was for cargo transportation to the ISS. SpaceX was the first to undertake these flights with its Dragon capsule launched atop the Falcon 9 rocket. After successful tests between 2010 and 2012, SpaceX's launch system undertook its inaugural cargo flight to the ISS on 22 May 2012. Orbital Sciences did the same with cargo flights of the Cygnus capsule/Antares launcher. The Antares rocket had a successful launch to LEO in April 2013, and the Cygnus spacecraft successfully rendezvoused with the ISS for the first time in September 2013. Both of these vehicles relieved the burden of reliance on the Russian Soyuz capsule and Progress cargo vehicles for ISS resupply.

Several successes have been registered since those events, most especially the continuing Falcon 9/Dragon and Cygnus/Antares flights to support the ISS. SpaceX has conducted 21 resupply missions with its Falcon 9/Dragon combination between September 2010 and the end of 2020 with only one failure. Cygnus/Antares missions to resupply the ISS have taken place 16 times, also with only one failure, between April 2013 and February 2021. Other firms appear to be on the verge of adding orbital launch capability for the ISS in the 2020s. As risky as this approach seemed when proposed by Augustine's panel in 2010, it is paying off a decade later.

The next step was a full-blown human space access capability first successfully tested in May 2020. With the successful launch of astronauts aboard the SpaceX Falcon 9/Dragon capsule to the ISS on 30 May 2020, the beginning of the end of this transformation took shape. Thereafter, four American astronauts docked with the International Space Station aboard SpaceX's Crew Dragon capsule, "Resilience," on 16 November 2020, to begin a new era of ISS operational flights using the Falcon 9/Dragon system.

It appears as if NASA and several commercial partners have successfully navigated a commercial way forward for space access, and its partnerships with SpaceX, Northrop Grumman/Orbital Sciences, and others are opening a new era of human spaceflight for the United States.

A Way Forward?

This ferment of ideas and broad set of actions encouraged through NASA's strategic stimulation of private-sector investment suggests that human spaceflight remains very much a part of the current human spaceflight transition from the Space Shuttle era. At present, there is a cacophony of competing ideas and projects present. Further human spaceflight could rise or fall based on the

Figure 11-5. Inaugurating a new age of NASA's human space access, astronauts Douglas Hurley (left) and Robert Behnken pause for a photo as they exit the Neil A. Armstrong Operations and Checkout Building at the Agency's Kennedy Space Center in Florida on 30 May 2020 for the first launch of a crew on the SpaceX Falcon 9/Dragon combination. (NASA, KSC-20200530-PH-KLS02_0041)

ingenuity of its advocates to fashion activities that could become commercially self-supporting. One senior analyst recently commented that in 40 years of watching space policy, he has not seen a more difficult situation than in the first decades of the 21st century.

Without question, space commercialization has followed a path of struggle, diversion, and progress. Regardless, it has also followed a path inexorably pressing forward—perhaps two steps forward, one step backward, and three steps sideways with nearly every development—but the change has been profound over the recent history of the Space Age.

President Obama's decision to rely on private-sector efforts to develop next generation human space access capabilities was a bold, controversial initiative. It represented a daring change in approach, one that has been more successful than many thought it would be when first begun. It resurrects something akin to the earlier NASA model of public-private relations; this time NASA has developed more equal partnerships with other organizations to accomplish its space exploration mandate. At this point in the history of human spaceflight, some 60 years after Alan Shepard made his first suborbital flight and John F. Kennedy challenged Americans to reach the Moon by the end of the 1960s, it is appropriate to consider the possible futures for American astronauts in space. No doubt, the reliance on commercial space access will make possible the continued utilization of the International Space Station. This will consume the lion's share of NASA human spaceflight activity through near the end of the 2020s. With sufficient diligence and resources, of course, virtually anything humans can imagine in spaceflight may be achieved, and a return to the Moon and perhaps a mission to Mars will result later in this century. All should be concerned, however, if neither sufficient diligence nor resources are made available for bold initiatives beyond Earth orbit.

EPILOGUE

Retrospect and Prospect

I have been asked many times for my top 10 list of NACA/NASA accomplishments. It is not hard to come up with my number 1, the Moon landing of Apollo 11. But what is second, third, fourth, and so on? There are so many, and they are all stupendous but often in different ways. The Cosmic Background Explorer and the pinpointing of the Big Bang in time and space is high on my list. So are the rovers on Mars. The X-15 program with its pathbreaking 199 flights over a decade, the Grand Tour of the outer solar system, and the digital flight deck of all aircraft since the 1990s make my list as well. The "tunnel rats" at Langley Research Center using the Full-Scale Tunnel there to increase the aerodynamic efficiency of virtually all aircraft since the 1930s is impressive. So is the screeching test of the hypersonic X-43 in 2004 at Mach 9.64. It is impossible to list a top 10 that everyone might agree on, but it is fun to try. I challenge all to give it a go.

Let me offer a little different approach, however. It comes via an anecdote. In the critically acclaimed television situation comedy *Sports Night*, about a team that produces a nightly cable sports broadcast, one episode in 2000 included a telling discussion of space exploration. The fictional sports show's executive producer, Isaac Jaffee, played by Robert Guillaume, was talking with his producer, Dana Whitaker, played by Felicity Huffman, about space exploration. Isaac told her, "you put an X anyplace in the solar system, and the engineers at NASA can land a spacecraft on it."[1] So what are on my list of the 10 greatest landings in NACA/NASA history? Apollo 11, Apollo 12, Apollo 13's safe landing on Earth after an accident en route to the Moon, first flight of the Space Shuttle, last flight of the Space Shuttle, Chuck Yeager's X-1 supersonic flight, Joe Wheeler's X-15 flight, every aircraft ever safely landing after a warning of wind shear, every aircraft ever landing safely during icing conditions; and all the landings on Mars. There are others; what are your favorites?

The history of the NACA and NASA has been remarkable for its many successes, but also for its enormous disappointments. Going from the Wright brothers at Kitty Hawk to the Moon in 66 years is a stunning accomplishment. The journey from stick and canvas airplanes to gleaming titanium flight vehicles that can reach the edge of space is no less stellar. Making aerospace activities more routine and less heroic in the most recent part of the Space Age has been equally surprising.

The NACA's contributions to flight between 1915 and 1958 were profound. Equally profound are the contributions by NASA since 1958 for both air and space. The research undertaken by engineers and scientists over time has pushed the boundaries about flight. The research pilots and astronauts have taken us along as they reached into the unknown. The imagery, moving pictures, and communications of what has been learned in the process have allowed all to be become vicarious explorers in our own rights.

Who knows what the future might hold? Only time will tell. In aeronautics we may well see hypersonic aerospace planes enabling transcontinental flights in minutes rather than hours. We may yet also see new technology for guidance and control of personal aircraft. Likewise, space exploration provides a window on the universe from which fantastic new discoveries may be made. Humans may well discover extraterrestrial life. They may set their eyes on the image of an Earth-like planet around a nearby star. They may discover some fantastic material that can only be made in a gravity-free realm. Perhaps they may discover some heretofore unknown principle of physics. Maybe they will capture an image of the creation of the universe. That is the true excitement of the endeavor.

The 21st century promises to be an exciting experience for many reasons, but air- and spaceflight offer a uniquely challenging set of possibilities. While other analysts might differ with my list, I would suggest that there are five core challenges for those engaged in spaceflight in the 21st century. Each of these may be traced far back in the history of the aerospace age and have served as perennial issues affecting all outcomes involving an expansive future beyond this planet.

The first of these challenges involves the political will to continue an aggressive space exploration and aeronautical research program. At a fundamental level, it is the most critical challenge facing those who wish to venture into space in this century. It is even more significant than the technological issues that also present serious challenges. Because most space activities have been sponsored by governments, governmental decision-makers have to agree that the expenditure of funds for exploration is in the best interest of the state. Without that political will, discovery and exploration cannot take place.

At the same time, an expansive program of space exploration has not often been consistent with many of the elements of political reality in the United States since the 1960s. Most importantly, the high cost of conducting space exploration comes quickly into any discussion of the endeavor.

Of course, there are visions of spaceflight less ambitious than some that have been offered that might be more easily justified within the democratic process of the United States. Aimed at incremental advances, these include robotic planetary exploration and even limited human space activities. Most of what is presently under way under the umbrella of NASA in the United States and the other space agencies of the world falls into this category. Increasing NASA's share of the federal budget, currently less than one penny of every dollar spent by the government, would go far toward expanding opportunities for spaceflight, but doing so will require the closer linkage of spaceflight activities to broader national priorities.

The second challenge is the task of developing multifaceted, inexpensive, safe, reliable, and flexible flight capabilities. Pioneers of air- and spaceflight believed that humans could make flight safe and inexpensive. Despite years of effort, however, the dream of cheap and easy flight has not been fully attained. Costs remain particularly high. Air travel still relies on flying buses that get us from one place to another but neither inexpensively nor without straining our emotions and overstressing many passengers. We might continue to use rocket propulsion and, with new materials and clever engineering, make a space launcher that is not only recoverable, but also robust. We might also develop air-breathing hypersonic vehicles, and thus employ the potentially large mass fractions that air breathing theoretically promises to build a more capable vehicle to reach space.

The third challenge revolves around the development of smart robots in the 21st century to fly in the atmosphere and to explore the vast reaches of the solar system. Humans may well travel throughout the solar system in ways unimagined by the first pioneers: that is, by not physically going at all. Using the power of remote sensing, humans could establish a virtual presence on all the planets and their moons through which those of us on Earth could experience exploration without leaving the comfort of our homes. Humans might not progress naturally toward the colonization of Mars in this scenario but would participate fully in an extensive exploration by robotic machinery. Because of this, the human dimension of spaceflight could take on a less critical aspect than envisioned by most spaceflight advocates.

One of the unique surprises of the Space Age that opened with Sputnik in 1957 has been the rapid advance in electronics and robotics that made large-scale spaceflight technology without humans not only practicable but also desirable. This has led to a central debate in the field over the role of humans in spaceflight. Perhaps more can be accomplished without human presence. Clearly, if scientific understanding or space-based applications or military purposes are driving spaceflight as a whole, then humans flying aboard spacecraft have little appeal. Their presence makes the effort much more expensive because once a person is placed aboard a spacecraft, the primary purpose of that spacecraft is no longer a mission other than bringing the person home safely. But if the goal is human colonization of the solar system, then there are important reasons to foster human spaceflight technology.

This debate has raged for decades without resolution. It started reaching crescendo proportions in the first decade of the 21st century as the ISS came online and discussions of future efforts beyond the Station emerge in public policy. Scientist Paul Spudis observed, "Judicious use of robots and unmanned spacecraft can reduce the risk and increase the effectiveness of planetary exploration. But robots will never be replacements for people. Some scientists believe that artificial intelligence software may enhance the capabilities of unmanned probes, but so far those capabilities fall far short of what is required for even the most rudimentary forms of field study." Spudis finds that both will be necessary.

The fourth challenge concerns protecting this planet and this species. During the 21st century humans will face three great environmental challenges: overpopulation, resource depletion (especially fossil fuels), and environmental degradation. Without air- and space-based resources—especially aircraft and remote sensing satellites that monitor Earth—humans will not be able to control these trends.

Humans can use air and space as a place from which to monitor the health of Earth, maximize natural resources, and spot polluters. By joining space with activities on the ground, humans have a fighting chance to protect the environment in which they live. Using space to protect Earth will be as important to 21st-century history as Moon landings were to the 20th. At the same time, humans will confront the consequences of environmental degradation *in space*. Orbital debris, derelict spacecraft, and satellites reentering the atmosphere have already created hazards around Earth. Proposals to strip-mine the Moon and asteroids make many people blanch; how dare humanity, having fouled Earth, destroy the pristine quality of extraterrestrial bodies? The environmental movement will move into space.

A final challenge will be the sustained human exploration and development of space. The creation of a permanently occupied space station has been realized through an international consortium. The first crew set up residence aboard the ISS in 2000. With this accomplishment, the spacefaring nations of the world intend that no future generation will ever know a time when there is not some human presence in space. The Station has energized the development of private laboratories, serving as a high-tech host of what is essentially an orbital "research park." This permits research not possible on Earth in such areas as materials science, fluid physics, combustion science, and biotechnology.

Using the Space Station as a base camp, humanity may sometime be able to return to the Moon and establish a permanent human presence there. It is no longer hard to get there. All of the technology is understandable to land and return. Such an endeavor requires only a sustained investment, and the results may well be astounding. Why return to the Moon? This is a critical question, especially because humans have already "been there, done that." There are six compelling reasons:

- It is only three days' travel time from Earth, as opposed to the distance to Mars of nearly a year's travel time, allowing greater safety for those involved.
- It offers an ideal test bed for technologies and systems required for more extensive space exploration.
- It provides an excellent base for astronomy, geology, and other sciences, enabling the creation of critical building blocks in the knowledge necessary to go farther.
- It extends the knowledge gained with the Space Station in peaceful international cooperation in space and fosters stimulation of high-technology capabilities for all nations involved.
- It furthers the development of low-cost energy and other technologies that will have use not only on the Moon but also on Earth.
- It provides a base for planetary defenses that could be used to destroy near-Earth asteroids and other threats to Earth.

From the Moon, humans might undertake a mission to Mars, but the task is awesome. There is nothing magical about it, and a national mobilization to do so could be successful. But a human Mars landing would require a decision to accept enormous risk for a bold effort and to expend considerable funds in its accomplishment for a long period. Consistently, only about 40 percent of Americans polled have supported human missions to Mars. In that climate, there is little political justification to support an effort to go to that planet.

Using Apollo as a model—addressed as it was to an extremely specific political crisis relating to U.S.-Soviet competition—anyone seeking a decision to mount a human expedition to Mars must ask a critical question. What political, military, social, economic, or cultural challenge, scenario, or emergency can they envision to which the best response would be a national commitment on the part of the President and other elected officials to send humans to Mars? In addition, with significantly more failures than successes, and half of the eight probes of the 1990s ending in failure, any mission to Mars is at least an order of magnitude greater in complexity, risk, and cost than returning to the Moon. Absent a major surprise that would change the space policy and political landscapes, I doubt we will land on Mars before the latter part of the 21st century.

Since the dawn of the aerospace age, humanity has developed and effectively used the capability to move outward. In the process much has been accomplished, some tragedies have occurred, and several challenges remain. Who knows what transforming discoveries will be made in the first part of the 21st century that will alter the course of the future? Only one feature of spaceflight is inevitable: The unexpected often occurs. Air and space are full of achievements, disappointments, and surprises. By going beyond, humans learn what they do not know and point to a hopeful future.

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Epilogue

1 "The Sweet Smell of Air," *Sports Night*, first aired 25 January 2000.

Acronyms

ABMA	Army Ballistic Missile Agency
ACES	Air Collection and Enrichment System
ACRIMSAT	Active Cavity Radiometer Irradiance Monitor Satellite
AEDC	Arnold Engineering Development Center
AERL	Aircraft Engine Research Laboratory
AST	Advanced Subsonic Technology
ATM	Apollo Telescope Mount
ATS	Applications Technology Satellite
AWT	Atmospheric Wind Tunnel
Caltech	California Institute of Technology
CCDev	Commercial Crew Development
CCiCaP	Commercial Crew Integrated Capability
CFD	computational fluid dynamics
CGRO	Compton Gamma Ray Observatory
COBE	Cosmic Background Explorer
CONTOUR	Comet Nucleus Tour
CSAGI	Comité Spécial de l'Année Géophysique Internationale
CXO	Chandra X-ray Observatory
DARPA	Defense Advanced Research Projects Agency
DC	Douglas Commercial
DFBW	Digital Fly-By-Wire
DOD	Department of Defense
DSN	Deep Space Network
EOS	Earth Observing System
ESA	European Space Agency
ESSA	Environmental Science Services Administration
EVA	Extravehicular Activity
F	Fahrenheit
FAA	Federal Aviation Administration
FST	Full-Scale Tunnel
FY	fiscal year

GALCIT	Guggenheim Aeronautical Laboratory, California Institute of Technology
GE	General Electric
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HiMAT	Highly Maneuverable Aircraft Technology
HRE	Hypersonic Ramjet Experiment
HSR	High-Speed Research
HST	High Speed Tunnel
HST	Hubble Space Telescope
IBM	International Business Machines
ICBM	intercontinental ballistic missile
IGY	International Geophysical Year
InSight	Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KSC	Kennedy Space Center
LACES	Liquid Air Collection Engine System
LACIE	Large Area Crop Inventory Experiment
LMAL	Langley Memorial Aeronautical Laboratory
LBJ	Lyndon B. Johnson
LEO	low-Earth orbit
LM	Lunar Module
MAVEN	Mars Atmosphere and Volatile EvolutioN
MER	Manned Earth Reconnaissance
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MISS	Man in Space Soonest
MIT	Massachusetts Institute of Technology
MPP	Massively Parallel Processor
MTPE	Mission to Planet Earth
NAA	National Aeronautic Association
NAA	North American Aviation, Inc.
NACA	National Advisory Committee for Aeronautics
NAS	Numerical Aerodynamic Simulator
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
NDRC	National Defense Research Committee

NEAR	Near Earth Asteroid Rendezvous
NRC	National Research Council
OAO	Orbiting Astronomical Observatories
OGO	Orbiting Geophysical Observatories
OMB	Office of Management and Budget
PARD	Pilotless Aircraft Research Division
PRT	Propeller Research Tunnel
PSAC	President's Science Advisory Committee
PTA	Parent Teacher Association
R&D	Research and Development
RA	Research Authorizations
RCC	reinforced carbon-carbon
ROLS	Recoverable Orbital Launch System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SRB	Solid Rocket Boosters
SSME	Space Shuttle main engines
SSTO	single-stage-to-orbit
STEM	science, technology, engineering, and mathematics
STG	Space Task Group
SWT	Supersonic Wind Tunnel
TIROS	Television InfraRed Observational Satellite
TOPEX	Topography Experiment
TPS	thermal protection system
TRMM	Tropical Rainfall Measuring Mission
TTV	Test Tow Vehicle
TWA	Transcontinental and Western Airlines
UARS	Upper Atmosphere Research Satellite
USAF	United States Air Force
VDT	Variable Density Tunnel
WMAP	Wilkinson Microwave Anisotropy Probe

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100 Essential Books on NACA/NASA History

(in Alphabetical Order by Author's Last Name)

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