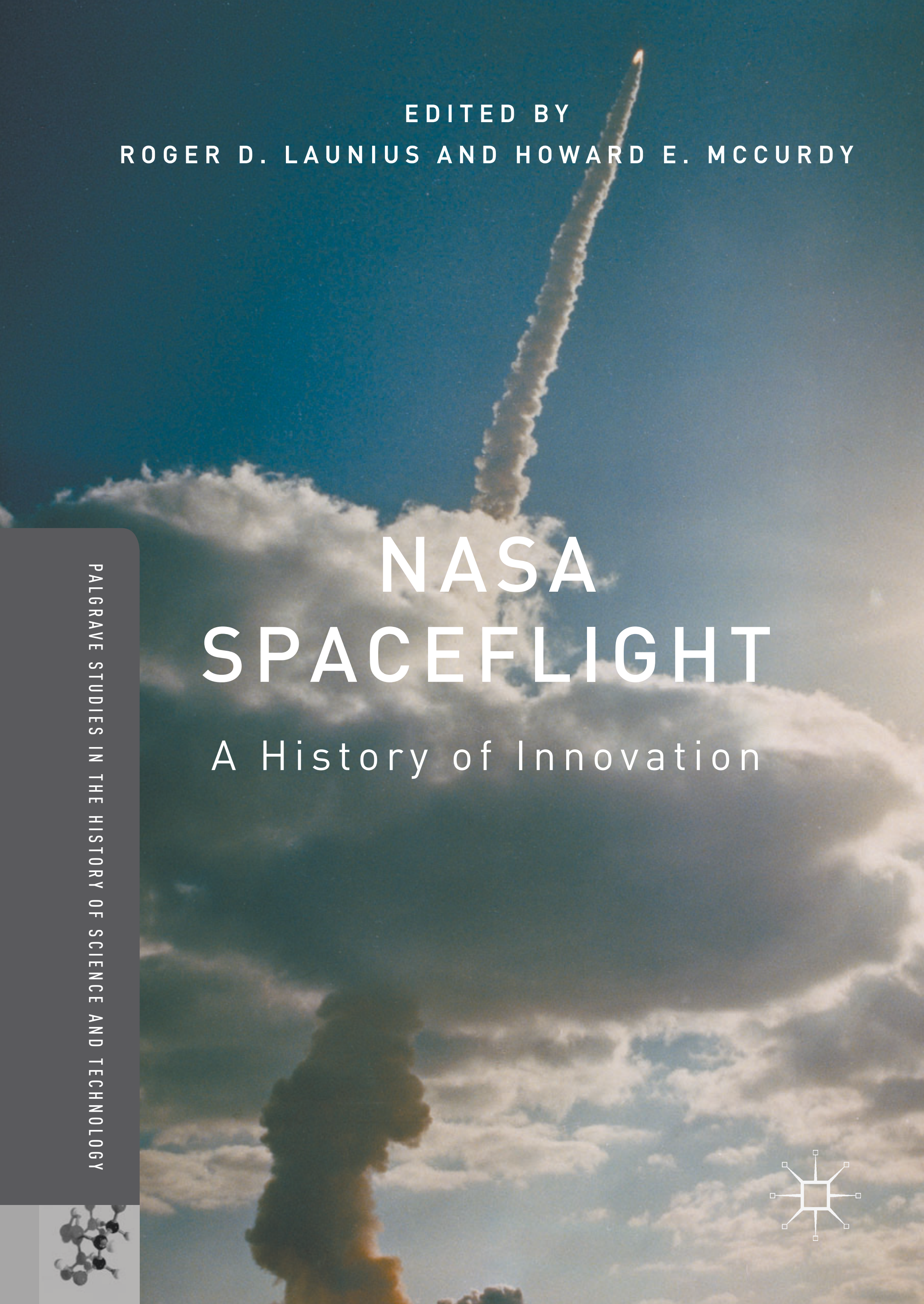

EDITED BY
ROGER D. LAUNIUS AND HOWARD E. MCCURDY

NASA SPACEFLIGHT

A History of Innovation

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Editors

NASA Spaceflight

A History of Innovation

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For
Margaret
and
Monique

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CHAPTER 1

Introduction: Partnerships for Innovation

Roger D. Launius and Howard E. McCurdy

Moore's Law encapsulates a number of economic and technological practices that have come to dominate modern economies. The power of imagination joined with the human capacity for tool-making leads to inventions that make various activities easier or more desirable. The steam turbine leads to the jet engine; the vacuum tube becomes the transistor; an eyeglass is transformed into a telescope.

Amplifying this trend, the economic theory of competition in an open market provides an incentive for providers to innovate. A firm that manufactures integrated circuits must increase the capacity of its product or reduce its cost (or both), or face the likelihood that the company will go out of business in a few years. Moore's observation specifically predicts that the number of transistors that humans can fit on an integrated circuit will double every eighteen months. If one firm does not do it, another will.

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An innovation can be a new idea that changes the way in which humans conduct their lives. It may take the form of an improvement in an existing device or process. Speaking generally, it typically makes some activity cheaper, faster, easier, more effective, or more accessible to a wider range of people.

When innovation occurs, the pace of change is often exponential. Its characteristics resemble an ever-ascending curve in which each new change becomes more profound than its predecessors. Two becomes four becomes eight and so on past one hundred. Eventually the pace of change becomes so rapid that the applications of new technologies become difficult to predict.[1]

Importantly, innovation contributes to economic growth. Economists estimate that approximately 70% of economic growth in the late twentieth century flowed directly from advances in information technology. In turn, economic growth promotes political stability, reduces government deficits, and allows societies to accomplish tasks they could not previously afford to undertake (like producing clean energy or traveling to Mars).[2]

Innovations that follow the characteristics of Moore's Law have affected many sectors of modern society. Such innovations have fostered the modern jet transport industry, propelled advances in the computer industry, revolutionized the broadcast of electromagnetic signals, reduced the risks of medical procedures, and produced the amazing world of nanotechnology.

A Characterization of Innovation

In twentieth-century America innovation has entered the lexicon of the success story, especially those stories associated with technology. And no society has been more enamored with innovation and what it might do for it or to it than modern America.[3] If there is one hallmark of the American people, it is their enthusiasm for technology and what it can help them to accomplish. Historian Perry Miller wrote of the Puritans of New England that they "flung themselves in the technological torrent, how they shouted with glee in the midst of the cataract, and cried to each other as they went headlong down the chute that here was their destiny" as they used technology to transform a wilderness into their "City upon a hill."[4] Since that time the USA has been known as a nation of technological system builders who could use this ability to create great machines, and the components of their operation, of wonder.

For the twentieth century no set of technological innovations are more intriguing than those associated with spaceflight. The compelling nature of this effort, and the activity that it has engendered on the part of many peoples and governments, makes the development of space technology an important area of investigation. Accordingly, there are many avenues of historical exploration at this juncture. Why did space technology take the shape it did; which individuals and organizations were involved in driving it; what factors influenced particular choices of scientific objectives and technologies to be used; and what were the political, economic, managerial, international, and cultural contexts in which the events of the space age have unfolded?

More importantly, how has innovation affected this technology? If there is a folklore in the public mind about the history of space engineering, it is the story of genius and its role in innovation. Americans love the idea of the lone inventor, especially if that inventor strives against all odds to develop some revolutionary piece of technology in a basement or garage. There have been enough instances of this in US history to feed this folklore and allow it to persist. The "Renaissance man" with a broad background who can build a technological system from the ground up permeates this ideal. We see this in the story of Robert Goddard and Elon Musk, though neither was as innovative nor as singular in his accomplishments as the public believes.[5]

Perhaps the central ingredient guiding the innovative process in space is the set of interrelationships that make up the enterprise. Since human beings are at the core of this enterprise, the complexity expands to include chance and nonlinear factors endemic to the real world of people. The challenge for the historian interested in the development of innovation is that these complexities make the innovation process exceptionally difficult to analyze and explain in a form understandable to any but the most probing specialists. The relationships between technological innovation; various institutions; innovative concepts, practices, or organizations; and the people associated with each are intrinsically complex. Essentially nonlinear, these relationships allow innovation to take place, no doubt, but there does not seem to be a way to guarantee it. Those who seek to command innovation find that changes in inputs to various aspects of systems, themselves designed to yield innovative alterations, do not necessarily ensure proportionate positive developments in output. It is nonlinearity writ large.[6]

Historians interested in innovation in aviation and spaceflight have much to learn from the sciences and the evolution of "chaos" theory. First developed as an identifiable unit of scientific theory in the mid-1970s, chaos theory asserts that the universe cannot be understood using standard approaches, but only with the acceptance of "nonrandom complicated motions that exhibit a very rapid growth of errors that, despite perfect determinism, inhibits any pragmatic ability to render long-term predictions."[7] The implications of these scientific theories offer profound opportunities for historians by suggesting that the world does not work in a deterministic, automatic fashion. They suggest that to all of the other factors that account for change in history with which the discipline has been wrestling since the beginning of the study of human affairs, we must add literally thousands of other independent variables not previously considered. As practitioners of an art, not a science, historians must, in coming to grips with aeronautical and astronautical innovation, understand and explain the complex interrelationships of institutions and cultures, myriad actions and agendas, technologies and their evolution, the uncertainties of conflict and cooperation in human relations, and the inexactitude of possibilities. That is a task not without difficulties.

The Innovation Process

Notwithstanding the complexity of the innovation process, and its inexact and nonlinear nature, both those engaged in seeking it and those recording it tend to seek order, clarity, and linearity. These are ultimately foolhardy goals, and the essays in this volume help to overcome this tendency by embracing the complexity and noting that even the actors in the innovation dramas depicted often did not understand the process. An opaqueness to the entire process frequently seems to be the most salient feature. To a very real extent, innovation in spaceflight is an example of heterogeneous engineering, which recognizes that technological issues are simultaneously organizational, economic, social, cultural, political, and on occasion irrational. Various interests tend to clash in the decision-making process as difficult calculations have to be made. What perhaps should be suggested is that a complex web or system of ties between various people, institutions, and interests shaped air- and spacecraft as they eventually evolved.[8] When these were combined they made it possible to develop machines that satisfied the majority of the priorities brought into the political process by the various parties concerned with the issue at the time, but that left other priorities untamed.

This raises the specter of Moore's Law once again. Those who question its applicability to spaceflight base their ideas on the US experience with rockets in general and spacecraft that hold human beings. Various attempts between 1972 and the present to reduce the cost of space transportation "by a factor of ten" did not materialize. With few exceptions, access to low-Earth orbit (LEO) in the first decade of the twenty-first century cost about as much as it did forty years earlier.[9] The expense of very large space facilities has not declined either. Space stations cost more per unit of mass then they did forty years ago. Since stations have grown in mass, their cost has accelerated commensurately.[10] Elected officials discontinued two human flight initiatives (the Space Exploration Initiative and Project Constellation) because their costs soared beyond the capacity of the government to finance them (Fig. 1.1).[11]

Yet during its history, NASA has supported a number of initiatives that have sought to reduce the cost of space flight or increase the amount of capacity that can be accommodated for a fixed cost. The Pathfinder lander and Sojourner rover that landed on Mars in 1997 cost much less than the Viking landers that arrived in 1976. The Spitzer Infrared Space Telescope (launched in 2003) cost less than the Hubble Space Telescope (launched in 1990). The first effort to orbit and land on an asteroid—the Near Earth Asteroid Rendezvous Shoemaker mission—cost less than the inflation-adjusted expense of the first autonomous spacecraft to land on the Moon.[12] Even adjusting for capability, these projects cost less than the missions that preceded them.

Such innovations often occur unnoticed in an agency dominated by human flight activities and large Cassini-class robotic missions.[13] They exist beneath the intense scrutiny afforded to the largest and most expensive activities. In part, the ability of participants on such projects to innovate may be due to the lack of attention those projects engender.

In 2006, with much fanfare, NASA officials announced their intention to provide support for a Commercial Orbital Transportation Services (COTS) initiative. The undertaking was initiated to encourage growth in the commercial launch industry, relieving NASA of the financial and operational burden of developing rocket ships with a final destination a few hundred miles above the Earth's surface. By partnering with commercial firms that would own and operate the equipment, public officials hoped to cut costs, accelerate development, and encourage innovation.[14]

Fig. 1.1 Early spaceflight required advances in propulsion, computer technology, and orbital rendezvous. Here the S-II stage of the Saturn V rocket is hoisted onto the A-2 test stand in 1967 at the Mississippi Test Facility, now the Stennis Space Center. This was the second stage of the 364 foot tall Moon rocket. The second stage was powered by five J-2 engines. (NASA, image number 67-701-C, public domain) (Available at https://www.flickr.com/photos/nasacommons/9457467017/in/album-72157650356082218/)

Public officials presented these partnerships as a new approach to spaceflight. Our point in presenting this book argues the contrary. Partnerships for innovation in the US space program are not new. They have been instituted since the first efforts at space flight a half-century ago. They tend not to attract as much external attention as more traditional undertakings like space stations and flights to the Moon, but they do exist. NASA has a long history of engaging in partnerships designed to encourage innovation and other objectives. Our task is to present some of that experience here.[15]

The Conventional Model

Project Apollo provided NASA and its public advocates with their most pressing model for exploring space. A large government agency, staffed predominantly with scientists and engineers, oversaw the development of rockets and spacecraft. Agency workers planned the missions, designed the machinery, and flew the spacecraft. Agency employees (a.k.a. astronauts) flew the spaceships. On the ground, agency workers directed launch and mission control centers.[16]

The agency relied upon large aerospace industries to fabricate the rockets, spacecraft, and other equipment. Nearly 90% of the funds allocated to Project Apollo went to industrial firms outside NASA providing products for the Moon program. In their public pronouncements, agency officials referred to the firms as partners or, more frequently, as the NASA–industry team. It was a partnership in name only, however. NASA paid the bills and officials at the government agency remained firmly in control.

To the people involved, the Moon program seemed highly innovative. Innovation in Project Apollo took the form of capacity-building. While President John F. Kennedy considered the proposal to send humans to the Moon during the spring of 1961, NASA attempted the first launch of an American into space. Astronaut Alan Shepard would not orbit the Earth, but merely travel on a fifteen minute parabola to the edge of space. The flight took place on May 5, 1961. A White House photographer took a picture of Kennedy and Vice President Lyndon B. Johnson intently watching the televised launch. Had the rocket exploded, or the mission otherwise failed, it is doubtful that President Kennedy would have made his famous proposal three weeks later before a joint session of Congress.

This was the state of American space flight at the point of Shepard's voyage. The Redstone rocket on which he rode, reconfigured with upper stages, was capable of placing a payload with a mass of 31 lb in orbit around the Earth. NASA astronaut John Glenn would not ride a larger rocket into orbit for another nine months. The flight computers for Shepard's voyage, reel-to reel IBM 7090s, filled Building 3 at NASA's new Goddard Space Flight Center.[17] Shepard's Mercury spacecraft contained a single seat and about as much usable room as one would expect to find in a very small bathroom shower stall.

Slightly more than eight years later, NASA astronauts Neil Armstrong and Edwin "Buzz" Aldrin stood on the Moon. They left the Earth on a rocket capable of placing a 260,000 lb (118 metric ton) payload in an orbit around the Earth. Their flight computer had a mass of 70 lb (32 kilograms), large by modern personal computer standards, but a huge advance in miniaturization for its time. Their two spacecraft possessed a usable internal volume of 369 cubic feet—ten times the size of Shepard's *Freedom 7*.[18]

Project Apollo was a triumph in capability. NASA officials spent $20.6 billion preparing for the voyage. They used the funds to design guidance and navigation systems. They established a tracking and communications network. They built field centers and a massive new launch facility in Florida. They designed, tested, and flew four rockets: the Little Joe II, the Saturn I, the Saturn IB, and the massive Saturn V. Through the Gemini project, NASA astronauts and flight controllers learned how to rendezvous and dock in space. Through the Surveyor project—a robotic precursor program—they learned that their astronauts would not sink into a thick mantle of lunar dust upon touchdown. They built and flight-tested various models of the new command and service module and lunar lander in Earth orbit before allowing astronauts to venture toward the Moon.

The actual flights to the Moon cost $4.6 billion, a fraction of the overall expense of the Apollo program.[19] NASA officials spent most of the funds allocated to Project Apollo building the capability to fly to and from the Moon, and they did so in only eight years.

Project Apollo became a blueprint for what the USA could do in space with a national commitment and adequate resources to complete the job. It also became a curse for future undertakings. After Project Apollo, resources were never sufficient to achieve imagined goals.

Exploration Without Innovation

Leaders of the 1969 Space Task Group, established to plan the US space effort beyond the Moon landings, proposed a space program that could be carried out if the USA maintained the level of public expenditures established by Project Apollo. With that degree of commitment, the group leaders professed, the USA could remain on the Moon and reach Mars by 1986. The report contained many goals for the civil space effort, including a new space transportation system, a space station, a large orbiting space telescope, and a robotic Grand Tour of the outer planets, but the principal feature was Moon–Mars.[20]

Here is the innovation strategy contained in the report of the Space Task Group. Continue production of the large Saturn V rocket, deriving savings from efficiencies of scale, and use the rocket to launch very large payloads. Continue flights to the Moon, building on existing capability. Develop a small space shuttle for transport of both crew and some of the materials to construct an Earth-orbiting space base, the latter assembled from upper stages of the Saturn V, placed in low-Earth orbit. Take the first steps toward human exploration of Mars.

The strategy built upon existing capability for the base program and invested in new capability for flights beyond. The expense of Moon flights had fallen dramatically after the Apollo 11 surface landing. The cost of the first three flights to the Moon (Apollos 8, 10, and 11) exceeded $1 billion, which when added to the preparatory expense of $20.6 billion pushed the total expenditure past $21 billion. The next landing (Apollo 12) cost less than $400 million. National wealth (measured by Gross Domestic Product, GDP) had doubled during the Apollo years, providing a deeper base on which to draw. The new strategy envisioned a 17-year effort, twice as long as Project Apollo. NASA cost analysts believed that the initiatives could be accomplished within a civil space budget that began at $5 billion and ran to about $24 billion by the 1980s (real-year dollars)—in essence a continuation of appropriation levels set during the Apollo years.[21]

The burden proved too great. Assessing financial burden in space exploration presents many challenges. Due to changes in the price of component goods over very long periods of time, comparisons are hard to make. As the economy grows, what looks like a huge burden from the perspective of the past becomes a light burden in the future. Advocates tend to mask the true expense of future projects by stating their cost in present-year dollars. NASA officials stated the budget estimate for the International Space Station (ISS), for example, at the value of the dollar in 1984, even though the USA was still paying for the facility in 2004 and beyond.

We suggest as a measure of burden the total program cost, in real-year dollars, as a share of national wealth in the year that the program began. Project Apollo cost $25.4 billion in real-year dollars, a generally accepted figure that maintains itself even under different methods of calculation. US GDP in 1961, when President Kennedy initiated the effort, stood at a modest $563 billion. Project Apollo thus represented a level of commitment equal to 4.5% of that year's GDP. We multiply the figure by 10 to represent its share in a GDP standardized to $1000. The number for Project Apollo thus translates to 45. The index represents a measure of relative burden: the higher the number, the heavier a burden the society is asked to bear.[22]

The Space Task Group proposal represented much more. By 1969, US GDP had grown to $1020 billion—the first trillion-dollar economy in the world. Continued spending at Apollo program levels for 17 years would make available for all civil space activities about $240 billion. That would provide at least $170 billion for a human space flight program.[23] Based on a $1 trillion economy, this sum extrapolates to an index of 167—nearly four times the burden of Project Apollo.

Subsequent analysis suggests that the figure proposed by the Space Task Group would have been insufficient to accomplish its various goals. It may have been enough to keep humans on the Moon while covering the Saturn V, the orbital base, and a small space shuttle, with their anticipated innovations. Yet it would have left little for the capability build-up for Mars.

A 1989 cost analysis suggests what those larger figures might be. NASA cost analysts provided figures for what was known as the Space Exploration Initiative (SEI). Like the 1969 proposal, the 1989 initiative was to return humans to the Moon and send more to Mars. Program advocates spread the expense over thirty-five years. NASA analysts attached their cost estimate to the so-called 90-Day Study, a reference to the length of time required to produce the mission plan. They produced one of the most carefully drawn estimates of a Moon–Mars undertaking, with adequate reserves, additive costs, and sufficient operational expenses. The initiative, the estimators concluded, would cost between

$471 billion and $541 billion. The figures were presented in 1991 dollars, not the real money that the nation would need to spend if the project went forward. Adjusting the annual outlays for actual and expected inflation through 2025 for the larger number produces a grand sum of approximately $965 billion.[24] Around Washington, DC, the proposal acquired a reputation as a trillion-dollar initiative.

Using the comparative index, the NASA response to the SEI represented an index rising to 171. Even though the economy had grown to $5.7 trillion by 1989, the effort required to engage in lunar and interplanetary human flight had risen with it. From Apollo onward, the indexes increased from 45 to 167 to 171.

To outsiders, this did not look like innovation. The civil space program seemed to be following Augustine's Law, not Moore's. Norman Augustine, a public official and aerospace executive, wrote a book in which he observed that the cost of individual military weapons systems rose exponentially while the US budgets for defense rose in a linear fashion. Only half-humorously, Augustine predicted that the weapon system curve would eventually intersect the budget curve, producing a situation in which the entire US defense budget would pay for one highly sophisticated jet aircraft.[25]

Reaction to the SEI cost estimate was swift and punishing. Mark Albrecht, executive director of the White House National Space Council, called the overall proposal unimaginative. President George H. W. Bush, who agreed to endorse the concept, announced that "I got set up." Senate appropriations committee chair Barbara Mikulski stated flatly, "we're essentially not doing Moon–Mars."[26]

For their next attempt, space advocates were more circumspect. In 2004, they convinced President George W. Bush to endorse a vision for space exploration that would return Americans to the Moon and dispatch them to Mars. This time, advocates did not offer a total program estimate, presenting instead a multi-colored "sand chart" that showed accumulating expenditures through 2020. The chart was easy to read, allowing anyone with the proper instruments (mainly a ruler) to determine the total program obligation through that year. The sum totaled a modest $178 billion, or an index of 15 based on that year's GDP of $12.3 trillion.[27]

The sum was barely enough to get Americans back to the Moon. Even so, it proved too much for an agency already preoccupied with the expenses of operating the NASA space shuttle and assembling the ISS. In

2010, President Barack Obama canceled all but two of the projects growing out of the policy and told NASA to confine its human deep-space exploration programs to as much as could be accomplished within a $4–5 billion annual appropriation. Mars remained as an ultimate destination, but only on a timetable that could be maintained within a modest outlay.

Compare this history to the reaction of a private-sector technology firm addressing a similar challenge. Gordon Moore, Robert Noyce, and Andy Grove founded the Intel Corporation in 1968. Their first product was a 64-bit memory chip. Moore believed that the ability of a new technology to replace an existing version required the new product to achieve a factor-of-ten improvement over the old, conventionally measured in the computer industry as cost per bit. While not quite attaining that goal, the Intel SRAM chip performed well enough to propel the company into a dominant position in the newly forming microelectronics industry.[28]

When a company produces a successful product, its competitors react in a predictable way. They copy it. At various points in the company's history, Intel executives responded by suing their competitors for infringement of intellectual property rights and lobbying the US Congress to enact a Semiconductor Chip Protection Act. The competitors sued back, alleging anti-trust violations. The limitations of this strategy became apparent when the Japanese semiconductor industry began manufacturing high-quality versions of Intel products. Intel incurred development costs that the Japanese avoided by simply manufacturing the chips. Lawsuits and lobbying cost money; foreign competition undercut sales. By the early 1980s, the company was in serious financial trouble. It could not maintain its dominant market position simply by selling modest improvements of old products.

In response, Intel executives adopted a more effectual strategy. They innovated. The company introduced products that were entirely new. In the 1980s, Intel undertook a major strategic shift and entered the microprocessing market, producing what would eventually become its highly successful Pentium microprocessor. Moore believed that constant innovation would keep the company alive and well. As a rule of thumb, he concluded that the company needed to introduce a new product every two years to stay ahead of the competition. Two years was faster than the competition could decipher, copy, and produce an old product. Moore's Law contains this insight. He believed that if his company missed a cycle or two, it would go out of business.

The market for NASA space products changed considerably in 1969. The immediate customers for any government product are the public officials who provide the appropriated funds for it. In 1969, President Richard Nixon responded to the proposals contained in the report of his Space Task Group. Parts of his response are worth quoting in full.

> We must think of [space activities] as part of a continuing process … not a series of separate leaps, each requiring a massive concentration of energy and will …. We must also realize that space expenditures must take their proper place within a rigorous system of national priorities. What we do in space from here on in must become a normal and regular part of our national life and must therefore be planned in conjunction with all of the other undertakings which are also important to us.[29]

In *After Apollo*, John Logsdon provides an extensive history of the proceedings leading to Nixon's statement and its subsequent consequences. Logsdon argues that the Nixon response created a fundamentally different national space policy, one that would dominate the nation's activities in space for at least the next half-century. No more great leaps. No more national burdens. No more crash programs. Nixon would not abolish the human space flight program. As Logsdon observes, Nixon admired the astronauts and NASA's achievements too much to do that. Nonetheless, under the Nixon doctrine the human space program would go only so far as NASA could propel it within a budget of limited means.[30] It was a perfect excuse for innovation.

In the years that followed, NASA failed to innovate. The burden of its human space flight programs increased from 45 for Project Apollo to 91 for the Space Shuttle and onward to 171 for the Space Exploration Initiative. Moreover, the willingness of elected officials to assume the burden imposed by Project Apollo was an anomaly, produced by a rare alignment of events that included the danger of nuclear exchange, public concern about the Cold War, the rocket as a mechanism for determining the outcome of the conflict, the reaction to Sputnik and the flight of Yuri Gagarin, the failed invasion of Cuba at the Bay of Pigs, a half-century of science fiction and popular science, and a new President determined to recapture national leadership. That alignment disappeared almost immediately after President Kennedy made his famous speech on May 25, 1961. Even Kennedy undercut the Moon race, suggesting that the USA abandon its quest in favor of a cooperative venture with the Soviet

Union and telling NASA Administrator James Webb, when Webb complained about budget constraints, that he (Kennedy) was "not that interested in space."[31]

As Logsdon points out, the Nixon doctrine provided the norm for America's human flight efforts in space. The much-heralded Kennedy doctrine was the exception and a rare one besides. It proved very hard to repeat, especially at a higher level.

NASA's Attempts to Innovate

Business firms face situations where the demand for their product declines. They face competition from rivals that can produce the item at a lower cost. Perhaps the rivals have not incurred the expense of invention and discovery. These are normal situations to which well-positioned business executives are paid to react.[32] In many cases, their reaction consists of producing a new product so attractive that consumers cannot resist the temptation to buy it.

That is what NASA officials responding to President Nixon's space doctrine promised to do. We say promised, because the commitment to actually accomplish the response was not firm. What the officials promised to do was dramatically reduce the cost of moving people and machinery to space, to make space flight so easy and inexpensive that no one with the means to support extraterrestrial travel would be able to resist the temptation to do it.

Members of the 1970 President's Science Advisory Committee, writing during the course of debate over the Nixon space doctrine and its consequences, suggested that the future of human space flight would likely be determined by developments in this realm. At the time, no one knew whether humans would prove more effective than robots for exploring space. If the cost of transporting humans and the machinery needed to keep them alive remained high, the future for human flight looked dim. If the cost fell, that would open up incredible opportunities.[33] Stanley Kubrick and Arthur C. Clarke visually represented the latter outcome in their classic 1968 film *2001: A Space Odyssey*. A winged space shuttle docks with a large rotating space station, a government official is transported to an existing lunar base, and astronauts depart on a human mission to the outer planets to look for evidence of intelligent extraterrestrial life.

At the time, a Saturn IB rocket could deliver a payload with a mass of 37,000 lb (16,600 kilograms) to low-Earth orbit at a cost of roughly $55 million. Engineers at NASA's Marshall Space Flight Center developed the Saturn IB to flight-test equipment for use in Project Apollo. The much larger Saturn V could place 285,000 lb (129,000 kilograms) in LEO for an estimated cost of $185 million for the rocket and $40 million more for flight operations. Thus, the cost per pound to LEO around 1970 ranged from $650 to $1500.

NASA officials agreed to cut that amount "by a factor of ten"—or, more accurately, they agreed to try. Estimates of the total program cost varied from $12.2 billion to $14.6 billion. Those sums included the cost of spacecraft design, fabrication of five spaceships, flight testing, and operational expenses covering up to 580 flights over a 12-year period.[34] The two figures were stated in 1970 and 1971 dollars, respectively. When translated into real-year appropriations, the lesser number produces a sum equal to $29 billion or an index of 27. Such an objective effectively achieved would have provided a technology irresistible to governments and firms in the spaceflight business.

In what has become an oft-repeated story, the effort failed. Initially, the program held to its cost goals. NASA met its cost goals for the first phase of the program (design, development, initial testing, and the production of the first two orbiters.) It actually spent $10 billion, a cost overrun of just 15%. It also met its shuttle operations cost goals for flights through 1990, spending $15 billion, 37% *under* the original projection.

Although the agency met its cost goals for operations, it could not achieve its desired flight rate. The plan called for at least twenty-four flights per year to achieve profitability; the goal was twice that number. The agency averaged six. This eliminated the prospects of marginal cost advantages arising from the opportunity to fly many times per year. When NASA officials tried to increase the flight rate, the *Challenger* exploded.

To achieve the desired flight rate, NASA officials planned to produce five orbiters. After production of the first two, the agency planned to refurbish *Columbia* and *Challenger* and produce three more. This phase of the program was estimated to cost $2.9 billion (1971 dollars). To meet these cost goals, NASA and its contractors needed to produce each new orbiter for about $625 million. The actual cost grew to $1 billion and beyond. Moreover, NASA kept incurring production costs. The original plan called for the agency to stop spending money on shuttle production after completion of the fifth orbiter and concentrate on operations. In fact, the agency continued to spend funds on shuttle production and upgrades through the year 2000, a total of $24.8 billion.

Under the original plan, NASA planned to replace the space shuttle with a more advanced vehicle in 1990. By 1990, with no replacement in sight, NASA continued to fly what had already proved itself to be a costly and inferior system for another twenty plus years. The cost per flight closed on $800 million as the challenges of flying what astronaut Michael Collins characterized as a "tender technology" became apparent. A private firm would have gone out of business; Congress continued to appropriate funds. In all, NASA spent slightly more than $81 billion on shuttle flight operations, far more than anticipated for the number of flights achieved.

In public discourse, the cost of the space shuttle program is often exaggerated. The program's Wikipedia page contains an estimate of $1.5 billion per flight.[35] The actual numbers are severe enough, though. In real-year dollars, the shuttle program consumed slightly more than $116 billion, an index (relative to 1972 GDP) of 91. Project Apollo, by contrast, scored 45. Had anyone known in 1972 that the shuttle program would impose a burden on the US space program roughly twice that of Project Apollo, the shuttle in its produced configuration would have never been approved.

Having endured the disappointment of the space shuttle, public officials repeated the experience. The original cost estimate for what became the ISS envisioned a modest facility requiring real-year appropriations of about $9.6 billion ($8 billion in 1984 dollars).[36] NASA spacecraft engineers possessed prior experience with orbital facilities, notably the Skylab workshop. Russian engineers had been flying small orbital workshops since 1971.

The Skylab initiative was particularly clever. Flight engineers converted the upper stage of a Saturn IB rocket originally built for the Apollo Moon program into an orbital workshop. They employed an unused Saturn V rocket to launch it. They commandeered three unused Apollo command and service modules for use as crew transfer vehicles and launched them on Saturn IB rockets originally developed for the Apollo flight test program. By building on previously developed equipment, the flight engineers were able to create a precursor space station with as much pressurized volume as a three-bedroom apartment at a cost of just over $2 billion, an index of 2.

However, NASA officials did not want to recreate Skylab; they wanted to build something more grandiose. Grandiose it was: a space station that topped $100 billion. The cost began with fabrication of major US station elements, a surprisingly modest amount. As anticipated in the original cost estimate, fabrication costs did not move much past $12 billion. Yet to that amount many additions applied. Between 1984 and 1993, the USA spent $10 billion on redesign activities, some of which were applicable to the configuration finally approved in 2004.[37] Transportation to orbit expenses accounting for the space shuttle alone totaled an estimated $31 billion. The cost of assembling the station and operating it between the first element launch in 1998 and 2014 added $32 billion. Analysts projected another $35 billion in operational expenses through 2024.[38] The international partners added more parts and flights, the value of which is difficult to ascertain, but may be in the $25 billion range. By agreeing to proceed with a large orbiting space station in 1984, the USA essentially agreed to commit $120 billion of its own funds over the next 40 years. These numbers represent the US contribution alone, in real-year dollars.

How could an agency that built a $120 billion space station present it in 1984 as costing $8 billion? First, the $8 billion covered only a fraction of the obligations associated with building and owning the facility. That figure included only the cost of station components and was in that respect an honest estimate. Transportation, assembly, maintenance, and flight operations added much more. Second, the number was stated in 1984 dollars, while the station was built with real-year dollars. The added costs precipitated delays in funding, which stretched obligations into future years where the difference between 1984 dollars and real-year money expanded. Third, the effort represents a failure in innovation. Rather than discuss more creative ways of conducting operations in orbit, station advocates chose to hide the true costs of commitment as a means of securing approval for the undertaking.

The shuttle/station experience effectively confined humans to low-Earth orbit for forty years. The $120 billion figure for the station created a burden of 30 points based on the 1984 approval year. As noted earlier, the space shuttle imposed a burden equal to 91. Together, station and shuttle imposed a burden on the US government *two and a half times* that of Project Apollo, relative to overall national wealth at their dates of approval (see Table 1.1).

Table 1.1 Relative burden of major US space programs

Program	*Index measure*
Space Exploration Initiative (1989)	171
Space Task Group (1969)	167
Space Shuttle (1972)	91
Project Apollo (1961)	45
International Space Station (1984)	30

The index represents the total program cost of the undertaking as a percentage of US Gross Domestic Product in the year that officials approved the initiative; or, in the case of unapproved programs, the year in which advocates proposed the undertaking. The resulting number is increased by a factor of ten to create a number based on a fixed GDP of 1000.

Space Exploration Initiative: $965/$5658 billion; Space Task Group: $170/$1020 billion; Space Shuttle: $116/$1284 billion; Project Apollo: $25.3/$563 billion; International Space Station: $120/$4041 billion.

Reflecting on the shuttle–station experience, NASA Administrator Michael Griffin observed that the money spent on the shuttle program alone would have supported six Saturn V rocket launches per year. In the final decade of shuttle operations, the shuttle–station configuration averaged $5.3 billion annually. That is more than the amount currently allocated to NASA's deep space human exploration effort. With the funds reallocated, Griffin grumbled, "we would be on Mars today, not writing about it as a subject 'for the next 50 years.'"[39]

Had a corporation like Intel failed to successfully innovate on two successive core initiatives, it would have disappeared. Griffin's statement reflected frustration more than expectation: the combined indices of the burden for the space shuttle and the space station fell short of the projected burden for going to Mars. Yet the statement contained one important insight. The failure to innovate on shuttle–station decisions did put NASA out of the deep space human exploration business for an unexpectedly long time. It also made doubtful the prospects for approving another government-built space station when the existing one disappears. Rather than use the two programs as a basis for continuing innovations in launch systems and habitats, NASA continued to pursue two programs that proved grossly inefficient relative to their original goals.

Pockets of Innovation

In retrospect, the shuttle–station programs were disappointing. Yet they did not reflect the capabilities of the agency overall. During this period, pockets of innovation did exist. They just did not receive as much attention as the disappointments.

We trace the pockets of innovation back to the creation of the agency. The Soviet Union launched Sputnik 1 on October 4, 1957. The USA attempted to launch its first Earth satellite on December 6, a product of the US Naval Research Laboratory. The rocket exploded on the launch pad. Anticipating difficulties, President Dwight Eisenhower had authorized Wernher von Braun, then the technical director for the Army's ballistic missile agency, to prepare a back-up plan. Von Braun brought out a three-stage Jupiter-C rocket (the first stage a direct descendent of the German V-2) for use as a launch vehicle. Officials at California's Jet Propulsion Laboratory (JPL), working with University of Iowa physicist James Van Allen, created a small satellite and attached it to a fourth-stage rocket motor. The group finished its work in 84 days, launching the first US satellite on January 31, 1958. President Eisenhower signed legislation creating NASA on October 1, 1958, eventually absorbing JPL and von Braun's division within the Army Ballistic Missile Agency. One could argue that NASA was born as a result of an act of innovation.

Concurrent with the unsuccessful effort to win funding for an ambitious post-Apollo spaceflight program, planetary scientists proposed a Grand Tour of the outer solar system. The scientists wanted to take advantage of a rare alignment of the outer planets that had not occurred since Thomas Jefferson was President. They proposed an expedition consisting of four robotic satellites that would visit Jupiter, Saturn, Uranus, Neptune, and Pluto, ready to launch in 1976–1977. The scientists estimated that the program would cost about $1 billion. Budget analysts in the Nixon White House fought to restrain NASA spending in the post-Apollo years. They suggested a scaled-back expedition that would visit Jupiter and Saturn. The cost savings were substantial. Jupiter–Saturn would cost just $360 million—about one-third of the projected estimate for the Grand Tour. Enthusiasm for the reduced objective was small, nevertheless. NASA already had made plans to dispatch two Pioneer spacecraft to Jupiter and Saturn in 1972 and 1973.[40]

Workers at JPL took the money. With it, they built two spacecraft designed to last decades, not years. *Voyager 1* encountered Jupiter and

Saturn; *Voyager 2* visited Jupiter, Saturn, Uranus, and Neptune. Both spacecraft continued to broadcast information as they approached the edge of the solar system four decades after program approval. They examined the interstellar wind on their distant travels.

Innovations helped the spacecraft do more work. *Voyagers 1* and *2* contained reprogrammable computers. Project workers asked the Atomic Energy Commission to produce radioisotope thermoelectric generators (RTG) that would continue to generate electric power for a half-century. Both spacecraft carried 3.7 meter high-gain antenna to communicate with NASA's Deep Space Network. "When you have less money," one NASA official observed, "you can even do better sometimes."[41]

Less was what public officials offered astronomers when the latter asked for a large infrared space observatory (later named the Spitzer Space Telescope). The Hubble Space Telescope inspired awe and wonder and $2 billion in development funds. The Compton Gamma Ray Observatory received respect. Public officials begrudgingly appropriated $1.6 billion for the Chandra X-Ray Observatory. When astronomers asked for more than $2 billion to design and build a fourth great observatory, the infrared space telescope, elected officials said no. NASA officials proposed a 12,500 lb (5700 kg) instrument with 3800 L of coolant to be launched on the space shuttle. Legislators said they might allow slightly less than $500 million.

Rather than lose the fourth great observatory, space scientists innovated. Through a combination of adjustments, they reduced the mass of the infrared observatory from 12,500 lb to just 1600. They reduced the amount of coolant the telescope needed, primarily by changing the telescope's position to a more thermally benign Earth-trailing orbit. A less massive instrument could be launched on a smaller and less expensive Delta 7920 rocket. Space scientists installed more advanced detection arrays, borrowed from heat-seeking military technologies. They used solid-state memory to increase data storage capacity. In all, the space scientists created an instrument with just 16% of the mass of the third great observatory at less than one-third of its cost. The telescope transmitted images in its cooled state from 2003 to 2009, twice the expected duration.

During the same period, similar developments caused the USA to revisit its space transportation policies. The resulting Commercial Orbital Transportation Services (COTS) program had its roots in two contradictory thoughts. The first dates back to the Space Shuttle and the history of transportation systems in general. Every great advance in transportation has been subsidized by government. Additionally, every great advance in transportation, beginning with the transcontinental railroad and proceeding through the automobile and aviation, has eventually gone commercial.[42] Space travel, advocates of the activity prophesized, would be no different. The desire to conduct commercial activities on the ISS amplified this belief. To embracers of the first thought, space transport to Earth orbit seemed to be on a path so routine and commonplace that the government no longer needed to do it. The first impulse for commercial transport grew out of the belief that space travel had matured to the point that the government presence could decline and the commercial presence could ascend. COTS sought to encourage this.

The second thought dealt with innovation. Space transport had proved so intractably risky and expensive that the government could not innovate its way to safer, cheaper flight alone. "Space launch is prohibitively expensive and risky," officials at NASA's Marshall Space Flight Center observed in explaining the Space Launch Initiative (the predecessor to COTS) in 2002: "Whether it's doing business in Earth-orbit or exploring distant worlds, the first few hundred kilometers are the toughest part of the journey."[43] Precisely because space travel was so difficult, a multiplicity of partners stood a better chance of improving cost and reliability than the government working by itself. The government could do technology research and business firms could seek efficiencies.

The second thought proved prophetic. The Marshall Space Flight Center released its statement in 2002. The following year, the space shuttle Columbia disintegrated on reentry. Public officials made plans to replace the shuttle with an Ares I rocket topped by an Orion space capsule, assuring US access to the ISS. A 2009 review committee observed that the Ares I rocket would require at least $5–6 billion to develop and, when combined with the Orion spacecraft cost, nearly $1 billion for each station sortie. Development costs were actually understated, since NASA flight engineers planned to assign all common expenses to the larger and even more expensive Ares V. The Orion capsule, essentially designed for deep space exploration, was over-engineered for trips to the ISS. The Ares I was under-engineered for trips beyond.

In 2010, President Barack Obama canceled Ares I along with the larger Project Constellation of which it was a part. In its place, he reaffirmed the previous administration's judgment that the private sector could do a better job of providing cargo and eventually crew transport to the ISS.

Governmental bodies are capable of great innovation. Radar, the mass production of penicillin, atomic energy, and the origins of the Internet are but a few of the examples of government-infused innovation. Yet business firms enjoy great advantages too. With the future of US civil space transportation at hand, it seems sufficient to say that frustration with governmental bodies and their contractors in the field of space transportation, coupled with the history of other transportation forms, prompted two separate administrations to pursue a partnership alternative. In the aggregate, public officials launched the commercial transportation initiative because of the hope that the private sector could make it safer, more routine, and less expensive.[44]

The consequences of the COTS decision are not yet known. In its earliest stages (cargo delivery to the ISS), the commercial approach did not demonstrate significant improvements over established forms such as the Russian *Progress* resupply vehicle.[45] The SpaceX cargo delivery contract (Fig. 1.2) provided Elon Musk's firm with $133 million per launch

Fig. 1.2 Partnerships such as those created between the federal government and the private corporation SpaceX frequently characterize successful efforts at innovation. President Barack Obama tours the commercial rocket processing facility of Space Exploration Technologies, known as SpaceX, along with Elon Musk, SpaceX CEO, at Cape Canaveral Air Force Station, Cape Canaveral, FL, on Thursday, April 15, 2010. (NASA/Bill Ingalls, public domain) (Available at http://www.nasa.gov/multimedia/imagegallery/obama_tour.html)

plus $396 million in seed funds.[46] At early stages of development, commercial aircraft often sell for less than their manufactured cost. The true test of profitability usually comes with repeated use. Repetition is key to eventual efficiency in space transportation.

Things to Come

The COTS experience awakened space flight aficionados to the potential virtues of commercial partnerships. Perhaps the arrangement offered a method to innovate a pathway out of the limitations imposed by the post-Apollo initiatives that cost too much or failed to attract sufficient funding. COTS required commercial partners to share in the financial burdens of developing something new. The commercial partners would fabricate, own, and operate the items they created. They could sell passage to all legal customers. The government provided seed money to help with development and promised to use the item as a prime customer. The seed money provided to commercial partners for their work in developing a new rocket was much less than the $5–6 billion that NASA sunk into the discontinued Ares I. In 2014, NASA selected two firms to provide prospective crew transport to the ISS.[47]

From these developments this study was born. We wanted people in the spaceflight community to know that NASA had been using various types of partnerships for more than 40 years. Partnerships that worked cut costs, promoted innovation, and provided program stability. Others proved less productive. The chapters that follow recount that history.

Surprisingly, the partnerships come in many forms. The conventional view of public/private partnerships posits a government agency partnering with a private-sector firm. Our study suggests the presence of many arrangements. Astonishing in their complexity, they more accurately resemble networks of cooperation than two-way collaborations. The arrangements fall into six broad categories. While this results in a co-production of knowledge and results, the co-production is much more than a simple two-sided relationship.[48]

In one of the earliest forms, NASA partnered with research laboratories to develop new products. For example, NASA officials relied on what eventually became the Charles Stark Draper Laboratory at the Massachusetts Institute of Technology to develop the Apollo guidance computer.[49]

NASA has used competitive mechanisms. In this respect, government field centers, university laboratories, and research institutes vie for government support by promising to promote innovation and restrain cost. NASA's Discovery program was initiated in 1989 for this purpose.[50]

The agency has offered services for reimbursement in a competitive marketplace. The original space shuttle pricing policy for commercial payloads adopted this approach.[51]

NASA officials have engaged in a wide range of interagency and international partnerships. Some international partnerships (such as those relating to the interagency relations governing Landsat and international communications satellite efforts) provide a means of cost sharing and a hedge against project cancelation. As a rule, however, such relationships do not provide a method for saving money.[52]

The space agency pioneered the use of cooperative ventures, often in the context of international relationships. The cooperative venture differs from the foregoing relationships in that NASA does not assume the position of the lead partner. NASA's first bilateral agreement that made possible the flight of Ariel 1 is a prime example of this approach. The British Science Research Council conducted the program; NASA provided the satellite and launch vehicle.[53]

Most significantly, NASA has entered into comprehensive commercial partnerships in which both sides contribute capital and share in the risks of development. The X-33/VentureStar project preceded the much publicized COTS effort.[54]

In addition, NASA has sought to innovate on its own. Development of the mission and launch control centers produced the "war room" model that has been reemployed for purposes as diverse as metropolitan governance and political campaigns. Though NASA officials sought to own the model, the complexity of the arrangement suggests that the own-your-own approach contains the seeds of cooperation and thus constitutes a seventh form.

This volume seeks to provide an overview of efforts such as these. No comprehensive history of the effort to innovate in NASA exists. There are some modest popular accounts, mostly designed to meet the needs of training in business and project management, but nothing of a scholarly nature.[55] One important book presents the spinoff argument, essentially questioning the proposition that government research spending produces useful commercial products. Yet it does not concentrate on NASA.[56] Our book examines the history of innovation in NASA, emphasizing case studies in which project leaders used various types of partnerships to promote new ways of exploring space. Some of these projects succeeded. Others failed. Some produced mixed results. All challenged the conventional method of doing the public's business in space.

Angelina Long Callahan tells the story of Ariel 1, a solar radiation satellite developed through a cooperative arrangement between the British Science and Engineering Research Council and the American National Aeronautics and Space Administration. The USA launched the satellite for the British government in 1962.

Roger D. Launius traces the relationship between the US government and the satellite communications industry in his review of global instantaneous communications. An industry–government consortium launched Telstar 1 in 1962, the first direct effort to establish satellite communications.

Paul E. Ceruzzi relates the development of the Apollo guidance computer. A significant step toward the miniaturization of computers, the project relied upon the traditional government–contractor relationship, in which NASA officials allowed experts at a leading research laboratory to address the challenge.

NASA officials turned to military predecessors to design their mission control centers. The history, retold by Layne Karafantis, shows how a government agency determined to run its own control centers nonetheless interacts with other organizations as the operation evolves.

The idea behind Landsat 1, launched in 1972, was fairly straightforward. NASA launched the satellite; a commercial industry would market the images. The arrangement became a full public/private partnership in 1992. Brian Jirout explains the complications that followed.

"We deliver." NASA officials believed that the space shuttle would become the launch vehicle of choice for commercial payloads. John M. Logsdon describes the pricing and marketing policies that the agency adopted to encourage commercial use in the early years of shuttle flight.

Matthew Hersch describes how NASA creatively reused the equipment left over from the Apollo Moon landings to develop two post-Apollo programs: the Skylab orbital workshop and the Soyuz rendezvous mission.

Logsdon returns with a history of the Orbital Sciences Corporation. Established in 1982, the company was one of the first to use public/private agreements as a basis for developing a commercial launch capability.

Company products included the Transfer Orbit Stage and air-launched Pegasus rocket.

Beginning in 1989, NASA sought to encourage low-cost innovation for planetary exploration by staging competitions among principal investigators at government field centers, research institutions, and universities. Michael J. Neufeld provides a history of the Discovery program in its ascent and decline.

Howard E. McCurdy tells the story of the X-33/VentureStar project, a joint venture between NASA and the Lockheed Martin Aerospace Corporation. Using a model that foreshadowed the COTS arrangement, the parties attempted to create a single-stage-to-orbit spacecraft to replace the NASA Space Shuttle. The partners canceled their joint undertaking in 2001.

A principal justification for the International Space Station was its role as a microgravity research laboratory for scientific and commercial investigations in space. Emily Margolis traces the effort to attract outside partners who would use the Kibo and Destiny research facilities through programs like NanoRacks.

The final case history returns to the program that inspired the much of the current interest in public/private partnerships. W. Henry Lambright describes efforts to establish a modern commercial Earth-orbital launch industry, variously known as Commercial Orbital Transportation Services (COTS) and Commercial Crew Development (CCDev).

To reach the Moon, the infant US space program had to transform itself from a collection of government research laboratories and rocket arsenals with workers accustomed to running small research projects using their own facilities into an organization capable of running mega-billion-dollar projects through conventional government contracts. It is fair to say that the agency that landed humans on the Moon in 1969 was a much transformed version of the organization that started the journey in 1961.

Spaceflight advocates have periodically tried to repeat the Apollo experience for other major new initiatives. The consequences, particularly for human spaceflight, have not been kind. Destinations beyond Earth orbit have proved elusive and activities in Earth orbit have crowded out funds that might have been used for human exploration beyond. Big spaceflight has resisted the types of cost and capability innovations that have characterized the telecommunications industry, the computer industry, and (one might add) most robotic space activities. Space travel in the Apollo mold has managed to escape the requirements of Moore's Law. This makes the prospects for activities like research stations on Mars problematic.

The ability to conduct large-scale, affordable spaceflight will require changes in the national space program as profound as those precipitated within NASA by Project Apollo. If humans reach Mars in the twenty-first century, it will be with organizations as transformed from traditional practices as was the NASA of 1969 from the agency in 1961. It had the same name, but massively different capabilities.

Public/private partnerships provide one option for change. Through this volume, we hope to show that the practice of using commercial and international partnerships to seed discovery in the US civil space program has a wider base than the more dominant experience with government-run Big Science might suggest.

Notes

1. A useful survey of studies of innovation may be found in Jan Fagerberga and Bart Verspagen, "Innovation Studies—The Emerging Structure of a New Scientific Field," *Research Policy* 38 (2009): 218–33.
2. See Lewis M. Branscomb, ed., *Empowering Technology: Implementing a U.S. Strategy* (Cambridge, MA: MIT Press, 1993); Lewis M. Branscomb and James H. Keller, eds., *Investing in Innovation: Creating a Research and Innovation Policy that Works* (Cambridge, MA: MIT Press, 1999); Bruce L.R. Smith and Claude E. Barfield, eds., *Technology, R&D, and the Economy* (Washington, DC: Brookings Institute, 1996); David C. Mowery and Nathan Rosenberg, *Paths of Innovation: Technological Change in 20th-Century America* (New York: Cambridge University Press, 1998); David C. Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (New York: Cambridge University Press, 1989); Nathan Rosenberg, *Exploring the Black Box: Technology, Economics, and History* (Cambridge, MA: MIT Press, 1994); Ray Kurzweil, *The Singularity is Near: When Humans Transcend Biology* (New York: Penguin, 2005).
3. This is the theme of the seminal study by Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (New York: Viking, 1989). For a broader perspective, see Benoît Godin, *Innovation Contested: The Idea of Innovation over the Centuries* (New York: Routledge, 2015).

4. Perry Miller, "The Responsibility of a Mind in a Civilization of Machines," *The American Scholar* 31 (Winter 1961–1962): 51–69.
5. See David A. Clary, *Rocket Man: Robert H. Goddard and the Birth of the Space Age* (New York: Hyperion, 2003); Clive Anderson, "Rethinking Public-Private Space Travel," *Space Policy* 28, no. 4 (November 2013): 266–71; Erik Seedhouse, *SpaceX: Making Commercial Spaceflight a Reality* (Chichester, UK: Springer Praxis, 2013; Stewart Money, *Here Be Dragons: The Rise of SpaceX and the Journey to Mars* (Burlington, Canada: Apogee Prime, 2014).
6. The complexity of nonlinearity in historical study has been discussed in its larger context in Bryan D. Palmer, *Descent into Discourse: The Reification of Language and the Writing of Social History* (Philadelphia, PA: Temple University Press, 1990), 188–206; Brook Thomas, *The New Historicism, and Other Old-Fashioned Topics* (Princeton, NJ: Princeton University Press, 1991), 24–50; Peter Novick, *The Noble Dream: The "Objectivity Question" and the American Historical Profession* (New York: Cambridge University Press, 1988), 415–628, passim.
7. Mitchell J. Feigenbaum, in Heinz-Otto Peitgen, Hartmut Jürgens, and Dietmar Saupe, eds., *Chaos and Fractals: New Frontiers of Science* (New York: Springer Verlag, 1992), 6.
8. John Law, "Technology and Heterogeneous Engineering: The Case of Portuguese Expansion," 111–34; and Donald MacKenzie, "Missile Accuracy: A Case Study in the Social Processes of Technological Change," 195–222, both in Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch, eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge, MA: MIT Press, 1987).
9. Roger D. Launius, "Between a Rocket and a Hard Place: The Challenge of Space Access," in W. Henry Lambright, ed., *Space Policy in the 21st Century* (Baltimore, MD: Johns Hopkins University Press, 2002), pp. 15–54; J.D. Hunley, *Preludes to U.S. Space-Launch Vehicle Technology: Goddard Rockets to Minuteman III* (Gainesville: University Press of Florida, 2008); J.D. Hunley, *U.S. Space-Launch Vehicle Technology: Viking to Space Shuttle* (Gainesville: University Press of Florida, 2008).
10. Relative to Skylab, an orbital workshop occupied periodically during 1973 and 1974, the International Space Station has three times the pressurized volume, seven times the mass, and ten times the cost. Skylab cost approximately $2.1 billion. Linda Neuman Ezell, *NASA Historical Date Book, Vol. III: Programs and Projects 1969–1978* (Washington, DC: NASA SP-4012, 1988) 63. The ISS does score highly on cost per astronaut day, but still falls far short of the imagined space bases with 50–150 occupants.

11. While the history of the Constellation program has yet to be written, a fine work on SEI is Thor Hogan, *Mars Wars: The Rise and Fall of the Space Exploration Initiative* (Washington, DC: NASA SP-2007-4410, 2007).
12. Howard E. McCurdy, *Faster-Better-Cheaper: Low-Cost Innovation in the U.S. Space Program* (Baltimore: Johns Hopkins University Press, 2001).
13. Michael Meltzer, *The Cassini-Huygens Visit to Saturn: An Historic Mission to the Ringed Planet* (Chichester, UK: Springer Praxis, 2015).
14. John M. Logsdon, "A New U.S. Approach to Human Spaceflight?" *Space Policy* 27 (February 2011): 15–19; Augustine Panel, "Seeking a Human Spaceflight Program Worthy of a Great Nation," October 23, 2009, available on-line at http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf, accessed 6/9/2015 1:04 PM; Amy Klamper, "NASA in Limbo as Augustine Panel Issues Final Report," *Space News*, October 23, 2009, available on-line at http://www.spacenews.com/civil/091023-nasa-augustine-panel-final-report.html, accessed 6/9/2014 3:31 PM; NASA Press Release 10-277, "NASA Seeks More Proposals On Commercial Crew Development," October 25, 2010, available on-line at http://www.nasa.gov/home/hqnews/2010/oct/HQ_10-277_CCDev.html. accessed 6/9/2015 4:32 PM; Chris Bergin, "Four Companies Win Big Money via NASA's CCDEV-2 Awards," April 18, 2011, available on-line at http://www.nasaspaceflight.com/2011/04/four-companies-win-nasas-ccdev-2-awards/, accessed 6/9/2015 4:35 PM.
15. This has been argued in Roger D. Launius, *Historical Analogs for the Stimulation of Space Commerce* (Washington, DC: NASA SP-2014-4554, Monographs in Aerospace History, No. 54, 2014).
16. There are many books on the history of Apollo. See Howard E. McCurdy, *Space and American Imagination* (Baltimore, MD: Johns Hopkins University Press, 2001 ed.), 93–119, for a discussion of this epoch in the history of spaceflight.
17. James A. Tomayko, *Computers in Spacecraft: The NASA Experience* (Washington, DC: NASW-3714, March 1988), 245.
18. NASA, Information Summaries, PMS 017-C(KSC), September 1991.
19. Howard E. McCurdy, Jason Robinson, and Shawn Janzen, "How much did we *really* spend to go to the Moon?" Public Policy for Innovation www.publicpolicyinnovation.com (2015).
20. Space Task Group, "The Post-Apollo Space Program: Directions for the Future," Report to the President, September 1969, copy in NASA Historical Reference Collection, NASA History Office, NASA Headquarters, Washington, DC.
21. Space Task Group: 22.

22. President Kennedy committed the USA to only one landing, an achievement generally set at about $21 billion. The lesser figure produces an index of 37.
23. Space Task Group: option 2, p. 22. Figures have been converted to real-year dollars.
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CHAPTER 2

The Origins and Flagship Project of NASA's International Program: The Ariel Case Study

Angelina Long Callahan

Introduction: Coordinating Among Emerging Centers of Space Science and Technology

The formation of NASA is conventionally presented as a consequence of two superpowers competing for dominance in space by consolidating their space activities. Based on the history of the Ariel series of US–UK satellites, this chapter illustrates how the complexity of scientific satellite systems demanded that innovation (the social processes by which institutions mastered and brought to practice novel designs and/or production) unfold as a process of collective learning.[1] Central to this narrative is the fact that this collective learning process is prolonged in nature and international in scope.

Throughout a formative period from 1945 to 1958, US scientist-administrators functioned as important mediators between scientific practice and national interest. These key figures coordinated rocket and satellite activities for the 1957–1958 International Geophysical Year (IGY) and later advocated strongly for the formation of NASA.

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Representatives of the US space science community recognized that space exploration was intimately linked to Cold War potency and that a robust space program hinged on international leadership—both a technical lead in contrast to other countries and the leadership ability to marshal resources of a plethora of organizations abroad.

In August 1957, one week after the launch of the first Soviet R-7 rocket and roughly five weeks before a modified R-7 would carry Sputnik 1 into orbit, representatives of the US Army, Navy, and Air Force research and development (R&D) centers laid out the needs of the US space science community, practices that would become a formal mandate with the formation of NASA: to maintain international leadership through a dynamic program; to strengthen their effort through long-range planning and funding; to broaden the base by engaging new university and nondefense organizations; for program coordination to be arranged by "workers in the field"; to support an international forum in the field; and to support appropriate joint programs.[2] In the months that followed, IGY researchers communicated these objectives to executive and legislative bodies—often in explicit contrast to calls for "space stunts and spectaculars."[3]

These IGY precedents were essential to "maintain United States preeminence in the important field of rocket upper air research and to realize maximum value from the program for purposes of national defense and scientific progress" and resonate with three key themes from this book's major findings.

Part I: The IGY Years. The world's first satellite systems emerged from the mission requirements of researchers working in federal R&D facilities. These researchers set specifications for and then oversaw systems integration throughout a prolonged proof of concept period, roughly 1955–1962. This is due, in part, to the fact that innovation in systems spanning such a broad range of sectors (metallurgy, microelectronics, computing, electro-optical sensors, propellant technologies, radio direction and ranging, telemetering, etc.) demanded input from hundreds of different firms.

Technical development could be accomplished by working with US industries and universities. However, to operate these systems, satellite command stations, data acquisition stations, and tracking stations all necessitated international partnerships of varying levels of coordination.

Part II: NASA Formation. **Innovation in organization and structure is at times necessary to bring forth meaningful advancements in science and technology (S&T)**. This is evident in the US formation of the Upper Atmosphere Rocket Research Panel (UARRP), which coordinated the design and use of US sounding rockets, the use of IGY structures to mobilize resources for satellite systems operation, and finally the formation of NASA as a means of organizing and supporting farsighted research programs. Of these three phases, NASA embodied a federal mandate for the space science community to coordinate resources more thoroughly with the armed services, private sector, universities, and international partners.

The 1958 Space Act directed repeatedly that the Administration minimize unnecessary duplication of effort, facilitate the sharing of facilities, and circulate relevant scientific and engineering information among other R&D communities.[4] This was at once a cost-saving measure and at the same time a means of reducing information asymmetries among the US government as a buyer, contractors, international partners, and other R&D communities.

Part III: The Ariel Years. The US executive and legislative branches' commitment to consistently apply resources over a long lead time was necessary to sustain the multi-sectoral transition of space systems from 1950s IGY prototypes to operational systems of the 1960s. The first generation of scientific satellites—the Vanguards, Explorers, Ariels, and so on—were in many regards prototypes for future operational satellite systems featuring longer useful lives and more durable subsystems. From these, researchers acquired a hands-on understanding of satellite systems. This experience would make them more effective designers, project managers, and contract officers when it came time for the US government to design and procure operational satellite systems for upper atmospheric science, communications, navigation, and remote sensing.

This was the organizational context in which the US and UK space science communities agreed to collaborate on the Ariel series of satellites. As of 1959, both countries were still beginning to grasp the design and operations of satellite systems, and their researchers anticipated many more years of collaboration between the two nations' emerging space programs.

The IGY Satellite Years: Coordinating Resources for Space Science

In 1955, complex machinations between the scientific community (Lloyd Berkner in particular) and upper echelons of the US defense establishment introduced a US mandate to build and operate a satellite for the IGY.[5] Essentially, two proposals were offered: the Navy promised a more complex, expensive, and longer lead time scientific satellite system, whereas the Army prioritized the thrift and quick turnaround of a minimal orbiter. During deliberations between the two systems, the space science community's advocacy efforts "complicated matters, because it created a new, powerful constituency for an instrumented IGY satellite." In so doing, they unwittingly buttressed the Eisenhower Administration's agenda to establish peaceful overflight for reconnaissance satellite purposes.[6] The Navy's project Vanguard was selected as the USA's contribution to the IGY. While funding for Vanguard was guaranteed by US intelligence priorities, the satellite system proper took shape as determined by the space science community.

When NASA's Goddard Spaceflight Center (GSFC) was formed in 1958, it inherited the people, programs, and practices of the Vanguard system. Vanguard blurred the lines between national and international asset, independence and interdependence. Strictly speaking all IGY satellites were either US or USSR projects, but institutions and individuals across the globe invested resources in making the Vanguards, Sputniks, and Explorers ever more useful scientific instruments as more research communities compared data and reviewed their analyses.

One of the major selling points of the Naval Research Laboratory (NRL) IGY satellite proposal had been all-weather tracking of satellites by radio, which would one day have applications for tracking missiles, noncooperative satellites, nonradiating satellites, and space debris. NRL sent radio physicist John Mengel to a number of Latin American countries to survey potential tracking sites and consult with local authorities for collaboration. The result was a first-generation "fence" of radio tracking stations from North America and across South America for high-precision tracking and prediction of US satellites circling the Earth in equatorial orbits. In July 1956, the NRL began training representatives from other countries in the operation and use of the Navy's Minitrack stations.[7]

In addition to the more sophisticated Minitrack network, satellite tracking data was also gathered by amateur radio operators receiving Mark II Minitrack signals and "Moonwatch" amateur optical observers—the latter particularly useful after a satellite exhausted its power supply and stopped transmitting signals back to Earth.[8] Eager for the best possible observations from their collaborators, US researchers provided carefully meted-out information concerning their satellite systems, including instrument data, launch information, and short-range prediction data. They also provided information about telemetry, including on-board transmitter characteristics, methods of data encoding and storage, feasibility of reception of telemetered signals by general observers, location of stations, and "recommendations … as to desirable sites for establishment of such stations by other countries." With this information concerning satellites and launches, partners could better provide radio and optical tracking services: visibility of satellites, observational methods, and operational information for radio systems.[9] Embedded within these agreements were both promises to international partners and requests of them, setting norms for standardizing scientific data and its circulation. This "quasi-standardization" made it possible at long last to begin to "connect up the rocket results with other IGY observations."[10] IGY agreements also set a carefully regulated example of national transparency with dual-use technologies.

Thus, bringing prototype satellite innovations to fruition linked R&D resources across the globe. Through collaboration, US researchers were shaping the policy and structure of other countries' R&D organizations—if not just by opening minds and government pocketbooks to the feasibility of investing space systems. As early as February 8, 1957, the British National Committee to the IGY was pursuing what it characterized as a "Long Term Artificial Satellite Program." This included plans for a permanent high-precision radio tracking station in the UK and a second in the Commonwealth and/or Mediterranean.[11] Indeed, by the close of the IGY, the UK could boast a total of 18 radio and optical tracking stations.[12]

UK researchers proved important partners in IGY planning and execution, marshaling resources in the UK, but also identifying collaborators in British colonies and former colonies. For instance, when University College of Ibadan, Nigeria contacted the British National Committee to the IGY with plans to participate in the IGY satellite program (already having recruited two electronics experts for tracking purposes), members of the Royal Aircraft Establishment (RAE, the UK R&D organization responsible for technical development and transition to industry of space and missile systems) and the Royal Society agreed to help Nigeria purchase RAE-developed tracking equipment for its station.[13] For ionospheric sounding by radio, the UK Department of Scientific and Industrial Research operated two stations in Britain, one in Singapore, and one in Port Stanley in the Falkland Islands. In addition to this it cooperated with Ibadan University College, Nigeria as well as the South African Council of Scientific and Industrial Research at a station in UK territory, Nairobi.[14]

Working alongside the Australian Department of Supply on the Combined UK–Australia Committee, RAE researchers played a key part in negotiating and opening the launch facility (and later home of a Minitrack facility) at Woomera, Australia.[15] From the dawn of the IGY, scientists worried about the paucity of rocket observations from the southern hemisphere. There were a few facilities scattered around Argentina and Antarctica, and a "very small meteorological rocket site" in New Zealand, but Woomera became unquestionably the main facility in the southern hemisphere.

The UK and Australian researchers exhibited a philosophy parallel to the US Upper Atmosphere Rocket Research Panel (UARRP). In order to best coordinate experiments and share limited sounding rocket payload space among universities and department of defense labs, the US armed services had in 1945 formed UARRP. As US researchers transitioned from using leftover V-2s to designing and procuring their own sounding rockets, UARRP became a valuable organization to compare notes on system performance, coordinate experiments, and circulate results among the armed services, university, and industrial partners. Both UARRP and the UK–Australian research bodies engaged in nonsecret work "to give scientists not engaged in defense work the opportunity of using the facilities provided by G.W. [guided weapons] developments to extend their fundamental knowledge of the upper atmosphere, thus providing a background of knowledge which may be of use in the future." In spite of the growing number of sounding rocket ranges, members of the UN Committee on Space Research (COSPAR) still worried that the distribution of launch sites was not "ideal for investigating a number of problems," indicating there would be much work to do after the close of the IGY.[16]

With the caveat that the UK was one of the most technically advanced nonsuperpowers participating in the IGY, it becomes evident how skills honed during the IGY illustrate the level of technical and scientific sophistication that could, at least potentially, be embedded in a presatellite scientific community. For instance, though the UK launched no IGY satellites, the RAE researchers could still "do" satellite science by observing passes of the Sputniks (the inclination of many US orbits was too low for RAE to track). With the launch of Sputnik-1, RAE's Robert Merson immediately began work on a program to determine Sputnik's orbit. Using RAE's Pegasus computer program to analyze satellite interferometry from an indigenous tracking system, RAE researchers began working to extend upper atmospheric theory at unprecedented altitudes. From this they divined useful information about the upper atmosphere, the Earth's geomagnetic fields, as well as the Earth's oblateness. IGY researchers were surprised to discover that satellite orbits decayed far more quickly than had been anticipated by soundings at balloon and sounding rocket altitudes. By documenting with high precision the rate of orbital decay, they estimated upper atmospheric density, finding it ten times greater than the predominant model.[17] Later, by tracking changes in orbital inclinations over time, researchers at RAE computed the speed at which the upper atmosphere rotates, finding its rotation to be faster than that of the Earth itself. In total, RAE personnel turned out fourteen papers derived from observing IGY satellite orbits, revolutionizing upper atmospheric physicists' understanding of near Earth space.[18]

These diverse IGY experiences and investments provided a foundation on which the UK space science and engineering communities would in time build and operate satellite systems with the USA, the European Space Research Organization (ESRO), and others.

NASA Formation: Research Coordination Sustainable Within the US Political Economy

As of 1957, the USA and the UK space S&T communities were in very similar states: limits to innovation were not so much in terms of human ingenuity or technical reverse salients as due to a lack of resources (and/or an absence of political will to fund a long-term national satellite program). IGY funding had brought together an innovative system of technologies, but by no means guaranteed a sustainable post-IGY scientific satellite program. Indeed, UARRP–IGY researchers had for more than a decade faced the paradox in which US leadership in fundamental upper atmospheric studies was necessary for national security, yet between 1945 and 1957, Department of Defense (DoD) sponsors had provided hot-and-cold support for sounding rocket research, more project-by-project than long-run and programmatic. More than one university sounding rocket research department faced the possibility of being shut down for lack of funds before and during the IGY.[19] William Kellogg, head of RAND's Geophysics Engineering Division, predicted to Congress in December 1957 that bringing together a National Aeronautics and Space Administration would "Allow a long term program of space research to be carried out without interference with or by the military requirements for missiles, etc."[20] UARRP researchers were not advocating compartmentalizing scientific research activities from the armed services, but rather that space science be given more time, resources, and organizational latitude to come to fruition.

Even before the IGY had formally begun, research administrators and project leads recognized that their funding needs had essentially exceeded DoD and National Science Foundation/IGY funding structures. Hand in hand with this was the realization that members of UARRP would need a more powerful organizational presence and a *mandate* to plan and carry out long-term space research in national and international forms. These sentiments were put forth in a report introduced at the opening of this chapter, including authors from all three armed services. Therein, researchers endorsed a variety of means to maximize economies of coordination: the exchange of sounding rocket range use with international partners, an international forum to exchange "results and ideas," and "attracting foreign scientists to work jointly with us."[21] Presuming that the USA would and ought to take the lead in cooperation, many US space scientists welcomed the advent of strong research partners who, as evidenced by the IGY years, could help fill gaps in geospatial observations and theory.

It is critical to note that such views among a few key leaders in the US scientific community resonated with an array of national priorities at that time: it won them the ear of Vice President Nixon and of Congress, and the support of the President's Science Advisory Committee.[22] The formation of NASA would take the IGY communities to new levels of international exchange as well as new levels of accountability to the US government. Whereas DoD sponsors had expected more predictable and direct paths from fundamental research to defense technologies, White House and Congressional sponsors were as of 1957–1958 more willing to fund basic research for its own sake—as a part of national innovation policy writ large, but also as a carefully postured diplomatic gesture. Thus, practices honed for economizing on limited UARRP and IGY resources—liberal data exchange, coordination of research efforts to avoid unnecessary duplication, and so on— could also be read as symbolic gestures, validating NASA's (read: the USA's) commitment to space for peaceful purposes and Cold War era transparency.

The formation of NASA constituted a reorganization and expansion of preexisting national resources for the USA to secure a sustainable position of international leadership in space. By advocating for the formation of NASA, a handful of IGY scientists were calling for a new social contract with the state: still coordinating with the armed services, but now directly accountable to Congress and the White House. Leavened by the post-Sputnik missile and satellite preparedness hearings and a sense of national consensus, NASA emerged from the loosely aligned UARRP bodies, their at times tenuous relationships with sponsors, and the successful scientific precedents of a temporary IGY. The organizational innovation of NASA fundamentally altered the trajectory of space science research in the USA. Through NASA's leadership role in collaboration with other nations, training programs, internships, export of testing regimes, subsidized access to launchers, and circulation of data, it altered the trajectory of space science research throughout the world.

Ariel Years, 1959–1981: The Collective Learning Process Sustained

Ariel 1 (Fig. 2.1) is commonly recognized as the first project that NASA negotiated, aligning with what have become identified as NASA's five hallmarks for collaboration.

1. Designation of a central agency for negotiation and supervision
2. Committing to specific projects as opposed to generalized or open-ended programs without an expiration date and/or end deliverable
3. No exchange of funds; partners cover their respective costs

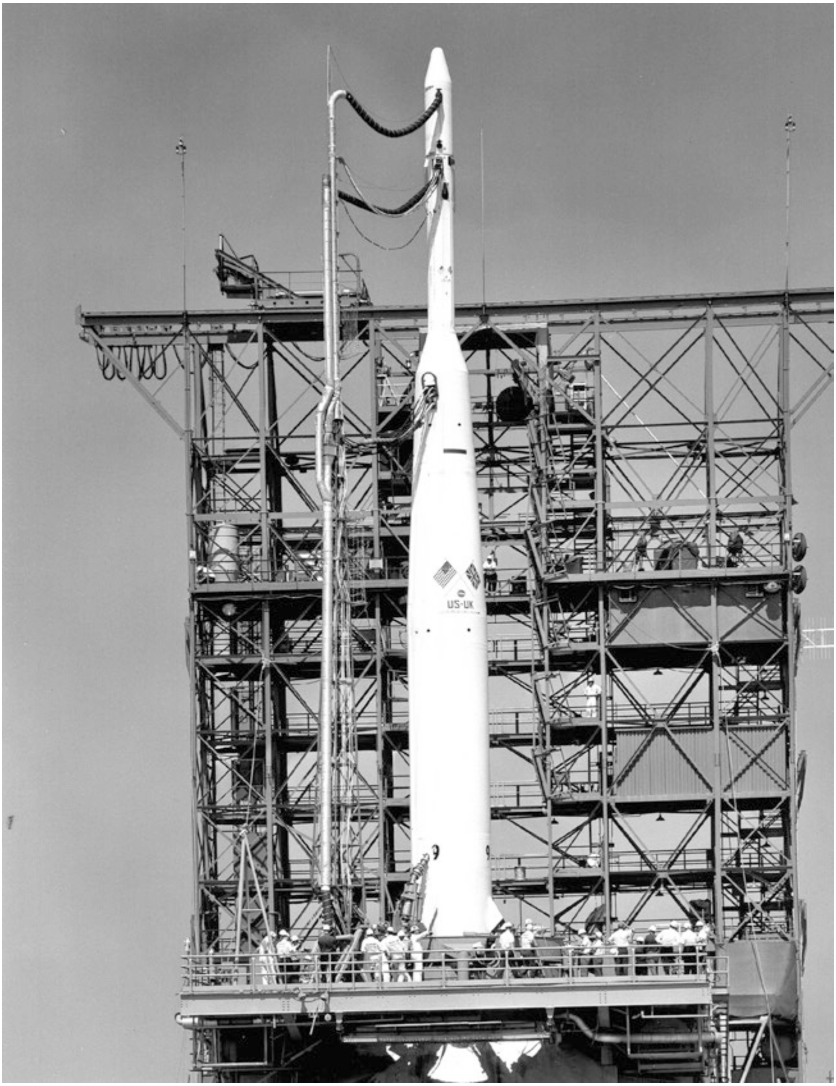

Fig. 2.1 A US Delta 9 rocket with the first UK satellite, Ariel 1, preparing for launch on April 26, 1962. (NASA, public domain.[56], Available at https://en.wikipedia.org/wiki/Ariel_1#/media/File:19620426_Delta_9-Ariel_1_LC-17A.jpg

4. Projects must be of mutual interest to NASA and its partners (and cannot be dismissed as merely "aid")
5. General publication/circulation of scientific results

In the wake of Sputnik and the formation of NASA, conditions born of a practice-based collective learning process took on new national and diplomatic significance. The USA–USSR space race ignited national security concerns abroad. Through the summer and fall of 1958, Harrie Massey, the Chief of the Ministry of Supply, and his colleagues labored to build a case for a strong UK space program.[23] Historian John Krige has explained how the US State Department (largely for reasons of Cold War politics) had hoped to make the UK the third nation to launch a satellite, but initially the British demurred in hopes of pursuing an independent launch capability.[24]

NASA (which would not formally open its doors until October 1, 1958) and its policy were still in a formative state when the USA made its first informal offer to collaborate, in September 1958. UK funds would run out on both the Skylark sounding rocket (which had been designed and procured by RAE for use in the IGY) and UK satellite work at the end of 1959, yet Massey remained optimistic. In October 1958, he put forth the proposal that the UK develop independent satellite launch capability. His memo, "UK Participation in Research with Artificial Satellites," advocated for adapting a military launch vehicle into a scientific satellite vehicle.[25] The next month, Homer Newell (former UARRP representative to the Special Committee on the IGY [CSAGI], Chair of the IGY Rocket Working Group, and NASA's newly appointed Assistant Director for Space Sciences) traveled abroad to attend a Royal Society event surveying the general state of space sciences and looking ahead to technical challenges. Massey led the discussion and the proceedings closed with Newell briefing his colleagues on NASA's program, holding up the US program as a model for space research (Fig. 2.2).[26]

In March 1959, NASA officials made a formal offer to the United Nations Committee on Space Research (COSPAR) inviting proposals for collaborative scientific satellites or isolated instrument packages to be installed on US scientific satellites. Newell called NASA Deputy Director Hugh Dryden from the meeting in the Netherlands, reporting that the COSPAR Executive Committee members requested more specific details as to what NASA could provide in a joint satellite launch.

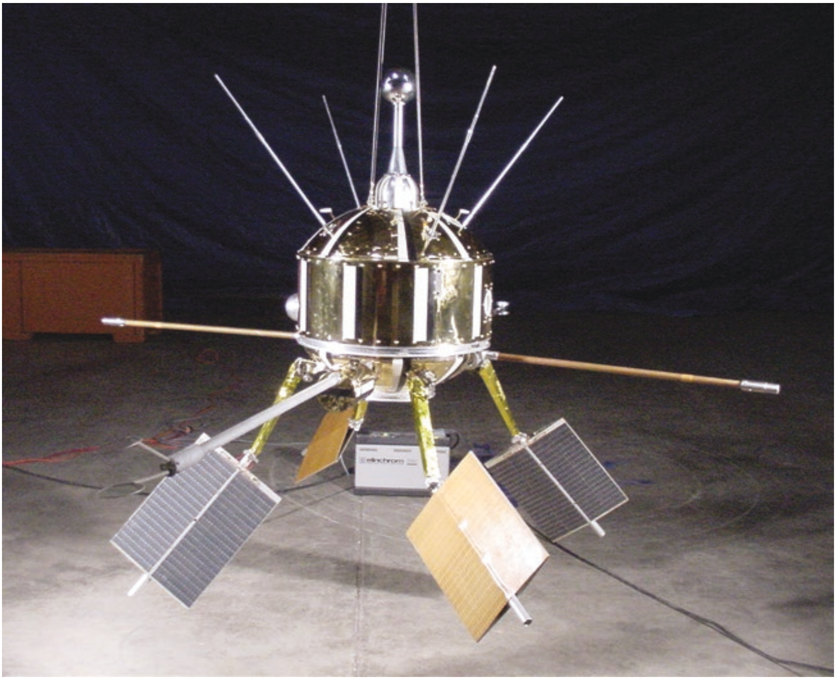

Fig. 2.2 A replica of Ariel 1, the world's first internationally conceived and executed satellite. The spacecraft carried six British experiments designed to study the ionosphere and its relationship to solar radiation, including cosmic ray, solar emission, and ionospheric experiments. The spacecraft chassis was built by the NASA Goddard Space Flight Center and launched on a Delta 9 launcher on April 26, 1962. (National Air and Space Museum, number A19751410000. Courtesy of NASM, Smithsonian Institution)

The two concluded that Newell could describe the general nature of available orbits; that a 150–300 pound payload "should be recommended by COSPAR"; and that the satellites should be acceptable to NASA.[27] The two estimated that the Scout booster (still under development) would be available in 1.5–2 years and might satisfy this requirement. Significantly, the memo to NASA Administrator T. Keith Glennan detailing this conversation did not address the degree to which the USA would help design, build, or test either the payloads or the satellite, only that it "should pass environmental tests prescribed by NASA."[28]

That April, the Ministry of Defense and Advisory Council on Scientific Policy announced that the UK would end its rocket development program. Massey and his colleagues would have to pursue satellite research through other means.[29]

Soon after, Massey came to the USA to determine preliminary grounds for what became the Ariel partnership. The extended IGY would come to a close in half a year and, with no plans for a satellite launcher, the UK satellite program faced a dimming future in space sciences.[30] That July, Massey requested that the UK pursue a satellite project in cooperation with the USA as a tutorial in which NASA performed systems integration of the British-built instruments and then provided launch services. Ariel would be a one-time "tutorial" for the partners transitioning from sounding rockets to satellites. NASA would provide launch services for all six platforms, while scientists and engineers in the UK gradually adopted from the USA responsibility for systems design, integration, testing, and operation.

Dryden and Glennan agreed that the tutorial element was "reasonable … at least for the first one or two vehicles." Glennan explained that the British were "simply taking on several of the scientific experiments which would ultimately be done by the US if the UK did not participate," his logic for the USA's cost savings.[31] As a "true cooperative program," in which "results of experiments be freely available to both participants … This would not mean that the US would censor or otherwise control the UK experiments." Dryden clarified that there would be no exchange of funds, though sources provide no evidence that the UK was asking for any aid.

It was possible for NASA to agree to launch an international satellite in part because of capabilities inherited from the Vanguard system: two rocket stages being integrated into the Scout launch vehicle, a growing network of tracking stations, computing centers, satellite power and communications systems, as well as testing and engineering regimes. The collective learning experience as these communities transitioned from sounding rockets to IGY satellite systems and then to Ariel satellites speaks to commonalities in form and function. US organizations like the National Advisory Committee on Aeronautics, Naval Research Laboratory, Jet Propulsion Laboratory, and Army Signal Corps labs (similar to the UK's Royal Aircraft Establishment) transitioned from aviation, to missile, to space research as vital centers through which national governments internalized information on cutting-edge technologies and emerging fields of science. The complexity, cost, and, later, the likelihood of bilateral monopolies within the aviation, space, and advanced weapons systems industries brought about technical organizations charged with maintaining a "smart buyer" capability throughout the innovation process. In this organizational tradition, NASA was brought together in part to function as a clearinghouse among proliferating organizations engaged in space S&T.

Through varied internalizations of the R&D process (hands-on partnerships, prototyping programs, R&D in areas of limited industrial interest), R&D centers such as these sought to remain knowledgeable independent assessors of contracts and contractors. An important part of their function was to interact with the world's state-of-the-art scientific and engineering communities, providing their governments with institutional memory over time and concerning a variety of firms, labs, and S&T fields.[32]

Thus, the IGY experiences of labs such as RAE and NRL (which would transfer its Vanguard team to NASA's Goddard Space Flight Center) provided a foundation of practice and experience for Ariel's execution.[33] For NRL and later NASA, the Vanguard satellite system was a prototype for building an in-house understanding of the parameters for design and use of tracking systems, launch vehicles, and scientific instruments. Even the Vanguard TV-3, widely identified as an abysmal failure, must be understood as one event within a rigorous (not flawless) first-of-a-kind development regime. The IGY years were rough for the US scientific satellite program, but they also provided many valuable lessons to engineering communities. Embedded in the transfer of the Vanguard system and staff to NASA was a decades-old culture of testing and evaluation, complemented by measured in-house fundamental research, and substantive collaborative development with industrial partners.

As US researchers alerted the budding UK sounding rocket researchers to their scientific and technical snarls, the US lead in satellite R&D would give the UK a leg up in managing and using scientific satellites. With extensive IGY/Vanguard satellite experience, GSFC researchers could provide more experienced "smart buyer" services to scientific satellite users such as university principal investigators and the US Weather Bureau, as well as international partners—a role continuing today.

All of these functions and expectations were implicit in the Ariel-1 satellite agreement. The actual deliverables for the program for which the R&D communities were accountable were framed primarily in terms of hardware development, testing, and operation. All policy matters were directed to Harrie Massey or Homer Newell (who transferred to NASA with the Vanguard team). All hardware concerns fell under the US Payload Manager, Robert C. Bauman (a research engineer from the Vanguard project), and the UK Payload Manager, M. O. Robins (of the Royal Society, acting through its COSPAR British National Committee on Space Research).[34] UK and US responsibilities were as follows:

- **UK responsibilities**: all sensors and electronics concerned with experiments up to telemetry input; environmental testing as outlined; all data analysis and interpretation
- **NASA (GSFC) responsibilities**: design, fabrication, and testing of prototype satellites and flight hardware structure (except UK environmental testing of scientific instruments), power supply, telemetry, command receiver, temperature control, data storage
- **Joint responsibility**: launch preparation, tracking, telemetered data, data handling, and data processing[35]

GSFC provided a power system featuring two nickel cadmium battery packets and four panels of solar cells. For telemetering data, a high-speed encoder sent data continuously to tracking and data recovery stations, while a low-speed encoder recorded data on tape and could be commanded by ground stations to play back as the satellite passed over the station's radio horizon.

UK research teams brought their own IGY experience to the table. Ariel's scientific instruments were selected based on their performance on Skylark sounding rockets (a call made in consultation with NASA partners).[36] J. Sayers' capacity probe measuring electron concentration originated in the Skylark program and was adapted "very successfully" for Ariel.[37] Likewise, the electron temperature and concentration probe used by Boyd and Willmore was based upon past models used to measure gas discharges, featuring several improvements to enhance precision and reliability. "Here was the heart of the cooperative enterprise in a substantive project," recalled NASA's Arnold Frutkin, "here was the mutual dependence and assistance, the give-and-take which alone could engender the intangible benefits of 'working together.'" Frutkin, who became NASA's head of International Programs after the Ariel agreement was made, argued that "the importance of the Joint Working Group is easily overlooked," though it bore responsibility for "successfully carrying out thousands of tasks which ultimately produce a total satellite and launcher system to be directed into space, carry out its intricate functions perfectly, bring new information to the experimenters, and reflect credit on the participants."[38]

In early March 1960, RAE director A. W. Lines brought three colleagues to visit NASA and industrial facilities. Researchers discussed standard operating procedures as well as problems with launch and design.[39] Following three weeks' travel, Lines delivered a glowing report. Glennan described him as "unable to believe thoroughly the broad scientific base that had been developed to support our satellite space program."[40] The USA was providing its partners with a great deal of information, but contact through projects such as Ariel, the UN Committee on Space Research, the International Scientific Unions, and professional organizations such as the Institute of Electrical and Electronics Engineers provided avenues through which NASA might, in the words of one report, "increase its direct contacts with foreign universities, industrial concerns, Government agencies, and individuals for direct acquisition of technical data."[41]

In February 1961, GSFC completed specifications for environmental testing of subassemblies, and transferred its standards of testing regimes from the USA to the UK.[42]

These testing regimes remained nearly unchanged from the Vanguard program and into the 1960s, and were transferred among a wide range of scientific and applications satellites.[43] In March 1962, RAE personnel visited GSFC to learn about experiments, encoders, and tape-recording technologies.[44]

Ariel 1 launched shortly thereafter.[45] Later in the spring of 1962, R.L.F. Boyd, ionospheric physicist and contributor to Ariel 1 (and later Ariels 2, 5, and 6), reported in a lecture that in the UK, "The vast experience already gained has [led] to the building up of both *know-how* and also of actual component assemblies of such systems as power supplies, amplifiers, oscillators, electrometers, encoder elements, timers, undervoltage systems, scalers, and so on." Contrasting the UK's grasp of space innovations with that in the USA, he observed that the "space physicist in the United States is able to draw on well-tried equipment for his experiment and is able, as he should, to give much of his time to the scientific aspects of the research." However, he did predict that "[w]ith the United Kingdom and

Europe now entering the field it is not too soon to start pooling knowledge and experience to prevent duplication of effort on purely technical development of the means of research."[46]

As suggested by Boyd, collaboration on the Ariel satellites left the UK with improved methods for the design of scientific satellites, systems integration, testing of satellite equipment, and better systems for analyzing data. With the Ariel satellite collaboration providing the seeds of innovation, RAE began to invest efforts in initiating, monitoring, and supervising R&D contracts in solar energy systems. It also began in-house work in calibration, measurement, solar cell qualification tests (a serious problem with US satellites), radiation damage studies, and advanced lightweight array development.[47] As of 1974, satellites powered by RAE/UK solar cells included Ariels 3, 4, and 5, Prospero, Miranda, ESRO 2 (ESRO), TD (ESRO), COS B(ESRO), Intasat (Spain), and Intelsat IV (international).[48]

RAE went on to fill important niches in satellite and rocket engineering, as well as space science, with more than one country benefiting from its in-house expertise. The RAE Space Department was involved in the design and construction of nearly all the British satellites of the 1960s and early 1970s. These included increasing responsibility for all six Ariel spacecraft (and then transitioning Ariel design and construction to industry), the Skynet military communications satellites (1 in 1969, 1B in 1970, and 2A in 1974), Prospero (1971) and Miranda (1974).[49] Paybacks to the international community included RAE's use of US DoD's NAVSPASUR satellite tracking data to improve its PROP program for scientific analysis of satellite orbits. From the dawning of the space age when RAE began using Sputnik's orbital calculations for upper atmospheric research until RAE was shut down in the 1980s, the researchers collected, calculated, and circulated data for the iconic "bible" of the orbits of satellites and larger space debris. The 1981 RAE Table of Earth Satellites fills more than 600 pages with estimations of shape, weight, size, perigree, apogee, eccentricity, and more of the world's satellite orbits. Due to its leadership in the science of orbit determination, upper atmospheric analysis, and geophysics, RAE asked Desmond King-Hele to organize an international meeting on the analysis of satellite orbits, proceedings with which it "set the seal of respectability" for scientific orbital analysis.[50]

Concluding Thoughts: Mutually Beneficial Coordination with the World's Lean Space Powers

Presenting Ariel as a culmination of a long and geographically distributed process of knowledge production (shaped by national priorities, personal ambitions, resources, and resource limitations among dozens of institutions), the intricacies of this collective learning process shed new light on the logic behind the formation of NASA. For too long NASA's origins have been reduced to the logic of space race tables (read: competition). One-upped by the Soviets twice in 1957, the USA reorganized, seeking to outdo its competitor and to demonstrate scientific and technological superiority through a series of seemingly home-grown space achievements.

Through this narrative, tracing NASA's origins to the coordinating bodies of sounding rocket researchers and barely touching on the varied contributions of the UK and partners in Australia, Canada, Nigeria, South Africa, New Zealand, Belgium, Norway, Ireland, Argentina, Singapore, and the Falkland Islands (to name a few), we can see how NASA is less a leader *of* and more a leader *in* an extensive network of research stations, labs, university teams, and firms. Competitive forces were certainly critical to building political consensus in favor of NASA's formation, but the practical considerations of reducing unnecessary duplication of effort, sharing expensive or geographically unique facilities, and coordinating research projects certainly provided the scientific precedents on which NASA was founded.

While nations lagging behind the USA's aerospace achievements viewed collaboration as an opportunity to narrow the "gap" in technical capabilities, all parties invoked the cost savings of collaboration to justify joint work. Furthermore, there were benefits from interoperability, standardization, or at least relative transparency. At the three-year anniversary of the IGY satellite Vanguard, one NASA official touted the long history of space scientists' cooperation and praised Ariel as a "small beginning," opining that it was "morally wrong … not to use foreign talent in space research."[51] Another official, speaking at the European Space Technology conference, said that resources ought to be pooled when costs are beyond the scope of individual countries,[52] and at the Inter-American Defense Board maintained that the cost and complexity of space exploration demanded "global efforts."[53] The NASA–DoD

Space Science Committee viewed cooperative programs as a means of developing "healthy, self-reliant space science programs in other countries."[54]

Given the UK's varied contributions to space science and technology, many former proponents of an indigenous UK space program continued to bemoan the fact that it had launched just one satellite on an "indigenously" developed rocket (Desmond King-Hele referred to the lack of a national space program as a "five-act tragedy"). In sketching out the broad base of engineering and scientific expertise taking shape in the UK, this chapter has illustrated how the UK was lacking not in terms of science and technology, but in political alignment with national priorities. Simply put, in spite of the advanced knowledge base already present, other national priorities took precedence over an "independent," "national" space program. Yet, significantly, the UK's space S&T base (distributed among universities, RAE, and increasingly, industry) went on to serve repeatedly as a valuable partner in cooperative programs with the USA and ESRO.

Having briefly outlined the process of collective learning that brought these nations into the space age, it seems fitting to ask just how exceptional the British experience was among the world's other spacefaring nations. It is quite clear that the UK experience is among the majority. As of 2013, of the 51 countries that had placed a satellite in orbit, only 10 had launched one through "indigenous" launch capability (not to some degree using another country for space access).[55] Was Britain third in the world or was it first among a new generation of lean space programs? Regardless of how the world's space powers are rated, they must be recognized at once as *states* vying for power among themselves and, still, as *governments* trying to bring order to the procurement and use of these systems—all within the limits of finite public resources.

Notes

1. Definition paraphrased from Richard Nelson, ed., *National Innovation Systems: A Comparative Analysis* (New York: Oxford University Press, 1993), 4.
2. Homer Newell, "The Challenge to United States Leadership in Rocket Sounding of the Upper Atmosphere," August 28, 1957, iii. This opens with a 15-page essay concerning the growing number of countries entering the field, including the fact that *rocketsonde* provides valuable observations for defense R&D, and provides eight recommendations for

maximizing the effort. It emphasizes the importance of fundamental research in R&D, as well as the value of coordinating work with international partners in basic research. Appendices summarizing research programs at US DoD labs provided by P.H. Wyckoff (Air Force Cambridge Research Center), W. W. Berning (Ballistic Research Laboratories), J. W. Townsend (Naval Research Laboratory), W. G. Stroud (Signal Engineering Laboratories), and N. W. Spencer (University of Michigan).

3. Angelina Callahan, "Satellite Meteorology in the Cold War Era: Scientific Coalitions and International Leadership 1946–1964" (Ph.D. thesis Georgia Institute of Technology, Atlanta, GA, 2013), 141–156.
4. NASA Space Act Unamended, PL #85-568, Section 203 a(2), a(3), b(6), b(8), b(10), b(11), b(12) Available at http://www.hq.nasa.gov/office/pao/History/spaceact.html.
5. Allan A. Needell, *Science, Cold War, and the American State: Lloyd V. Berkner and the Balance of Professional Ideals* (Australia: Harwood Academic Publishers, 2000).
6. Michael Neufeld, "Orbiter, Overflight, and the First Satellite: New Light on the Vanguard Decision," in Roger D. Launius, et al., R*econsidering Sputnik: Forty Years Since the Soviet Satellite* (New York: Routledge, 2000), 231–257.
7. William Corliss, Histories of the Space Tracking and Data Acquisition Network (STADAN) and the Manned Space Flight Network (MSFN) and the NASA Communications Network (NASCOM), NASA CR-140390, 24.
8. Ibid., 6–56. Mark II Minitrack System. For "relatively simple 'amateur type'" radio stations to track satellites, see Roger Easton, Project Vanguard Report No 21 Minitrack Report No 2, The Mark II Minitrack System, September 1957 (Washington D.C., NRL); for optical tracking, see Patrick McCray, *Keep Watching the Skies: the Story of Operation Moonwatch & the Dawn of the Space Age* (Princeton, NJ: Princeton University Press, 2008).
9. "Draft of preliminary proposal for data interchange in the IGY Rocket and Satellite Programs," Lloyd V. Berkner, Reporter for Rockets and Satellites December 19, 1956. File USNC Member File, Newell H. E., Technical Panel on Earth Satellites Program Correspondence, National Academies of Sciences, Washington, D.C.
10. Newell 1957, 12.
11. British National Committee to the IGY Artificial Satellite Subcommittee Minutes, February 8, 1957, Folder 118 England, Box 54, Sydney Chapman Papers, Niels Bohr Library and Archive, American Institute of Physics, College Park, MD (hereafter: Chapman Papers).
12. Harrie Massey, *History of British Space Science* (Cambridge, UK: Cambridge University Press, 2009), 49.

13. British National Committee for the IGY Artificial Satellite Subcommittee, February 8, 1957, Folder 118, Box 54, Chapman Papers.
14. British National Committee for the IGY, "The United Kingdom Contribution to the International Geophysical Year (1957–1957) Draft Introductions," date not legible. Folder 118 England, Box 54, Chapman Papers.
15. Upper Atmosphere Rocket Research Panel Report #41, June 2, 1955, Folder 252, Box 60, Chapman Papers.
16. Maurice Dubin, Preliminary Draft Report to COSPAR Working Group II "Sounding Rocket Facilities" Folder 174 Jule Charney, Chapman papers; David H. DeVorkin, *Science with a Vengeance: How the military created the US Space Sciences After World War II* (New York: Springer-Verlag, 1992).
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22. Homer Newell, *Beyond the Atmosphere* (Washington, DC: NASA SP 4211, 1980), 39–49; James Killian, *Sputnik, Scientists, and Eisenhower: A Memoir of the First Special Assistant to the President for Science and Technology* (Cambridge, Mass: MIT Press, 1977), 238–39, 124–28; Zuoyue Wang, *In Sputnik's Shadow: The President's Science Advisory Committee and Cold War America* (New Brunswick, NJ: Rutgers University Press, 2008), 88–97.
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25. Massey 2009, 455.
26. *Proceedings of the Royal Society. Series A* 253: 1275, 462–541.
27. There is a typo in Exploring the Unknown II: the original document lists the weight as maxing out at 300, not 500 pounds; Memorandum for T. Keith Glennan from Hugh Dryden, CC Dr. Killian's Office, March 12,

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28. Memorandum for T. Keith Glennan from Hugh Dryden, CC Dr. Killian's Office, March 12, 1959, RN 5661 Ariel 1 13/3/3, NHRC.
29. John Krige, "Building a Third Space Power: Western European Reactions to Sputnik at the Dawn of the Space Age" *Reconsidering Sputnik*, 299.
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36. John Krige and Arturo Russo, *Volume 1 The Story of ESRO and ELDO, 1958–1973* (The Netherlands: ESA Publications Division, 2000), 380.
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39. T. Keith Glennan, *The Birth of NASA* (Washington, D.C.: NASA SP-4105, 1995), 87.
40. Ibid, 110.
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47. RAE Technical Report 74159 Work in UK on the Applications of Solar Cells in Space (Ministry of Defense: Farnborough, 1974), 3.
48. Ibid, 11.
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50. Ibid 136, 118.
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52. Arnold Frutkin, "US Cooperation in Space Research" NASA Release No. 61–143.
53. Arnold Frutkin, Statement to Members of the Inter-American Defense Board, February 16, 1960, NASA Release No 60–124.
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CHAPTER 3

Global Instantaneous Telecommunications and the Development of Satellite Technology

Roger D. Launius

There has been no greater means of "supertribalization," the creation of recognized continuity in social relationships across time and space, than satellite communications.[1] Communications satellites have represented, for futurist John Naisbitt, the essential enabling technology of the post-modern world.[2] Marshall McLuhan and Bruce R. Powers further observed, "The wired society epitomized historically by telegraph and telephone links has, since the early 1900s, been slowly encapsulated by a wireless canopy of long-distance radio, microwave, and satellite. Coaxial cable has been obsolesced." The decentralization of information and authority brought on by satellite communications, according to McLuhan and Powers, "highlight[s] diversity and fragmentation."[3] Yet McLuhan and Powers also saw cause for concern. The "satellite turns the user into discarnate information. … What is really new about the satellite is that it intensifies the process of being everywhere at once." This

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presents a world of greater knowledge and interaction, but also one of more limited relationships.[4]

Regardless of interpretation, no space-based technology has been more significant, and more obvious, than satellite telecommunications. It transformed the world in the last decades of the twentieth century and continues to redefine everything in the twenty-first. Indeed, one could make the case that the most significant change to the life of the ordinary Earthling coming from an ability to fly in space is global instantaneous telecommunications. This is made possible by the constellations of communications satellites in Earth orbit. Without them, there would be at best a limited Internet, much less real-time news and sports coverage worldwide, and a lack of a host of other capabilities that have come to dominate our lives.[5]

Whether our lives would be significantly better or worse if this capability did not exist is problematic, but certainly it would be quite different. Some of us might well believe such changes to be a positive development, though most would not want to return to problematic global communications. The point, of course, is that the past did not have to develop in the way it did, and that there is evidence to suggest that the larger space program pushed technological development along certain paths that might have not been followed otherwise, both for good and for ill. It remains to be seen how historians might seek to analyze the overall impact of satellite communications on American lifestyles a century from now.

This chapter recounts the story of NASA and the larger role of government, in relation to private industry, in the development of satellite communications. To bring it about some very specific public policy, technology, and public/private relationships had to be developed. AT&T was committed to developing and operating its own communication satellites, insisting on extending its US monopoly into space. Politicos on all sides of the issue had different perspectives. NASA, charged with developing the technology and launching the satellites, sought to negotiate these divergent policy positions. Moreover, the potential for partnership was great, but not always effectively pursued. The result was an unusual set of policy choices, as well as inertia that led in some cases to technological and commercial stagnation, and only with the establishment of later public/private partnerships did an industry that everyone knew as an imminent possibility emerge in the latter 1960s.

John R. Pierce and the Bell Laboratories Satellite Telecommunications Initiative

The first commercial activities in space resulted from the efforts of the telecommunications industry to extend operations beyond the atmosphere, almost with the beginning of the space age. Indeed, satellite telecommunications was the only truly commercial space technology to be developed in the first decade after Sputnik. Space visionaries had long understood that satellites in Earth orbit could transform the nature of communications. Arthur C. Clarke wrote both fiction and popular scientific studies relative to space flight, physics, and astronomy. He posited in 1945 that three satellites placed in geosynchronous orbit 120 degrees apart could "give television and microwave coverage to the entire planet."[6] Later that same year, Clarke elaborated on the communications implications of satellites and set in motion the ideas that eventually led to the global communications revolution of the space age.[7]

Perhaps the first person to champion the technical and financial aspects of satellite communications at the beginning of the space age was John R. Pierce of AT&T's Bell Telephone Laboratories (Fig. 3.1). Pierce's studies in the early 1950s, although probably not spurred by Clarke's insights, laid out the technical requirements for the first active space communications satellite. In a 1954 speech and 1955 article, he explored the possibility of using what he called a communications "mirror" in space, a medium-orbit "repeater" that would reflect a signal from an Earth station back to another Earth station, and a geosynchronous "repeater" that remained at the same spot over the globe at all times.[8] Historian David J. Whalen concluded:

> In comparing the communications capacity of a satellite, which he [Pierce] estimated at 1000 simultaneous telephone calls, and the communications capacity of the first trans-Atlantic telephone cable (TAT-1), which could carry 36 simultaneous telephone calls at a cost of 30–50 million dollars, Pierce wondered if a satellite would be worth a billion dollars.

Pierce much later allowed that he had under-estimated its value by billions of dollars.[9]

In 1959, Pierce and a colleague at Bell Laboratories, Rudolf Kompfner, published the most detailed study of the subject yet offered in the open

Fig. 3.1 John R. Pierce of AT&T's Bell Telephone Laboratories was central to the development of satellite communications. He envisioned a network of satellites providing global instantaneous telecommunications, played a role in NASA's Project Echo, a passive communications satellite, and worked to build and launch Telstar 1, the first active-repeater satellite. (NASA, public domain. Available at https://www.nasa.gov/directorates/heo/scan/images/history/March1952.html)

technological literature. In it they questioned passive satellite communications systems, such as NASA's Project Echo, but advocated for an aggressive effort to develop electronic telecommunications systems in space.[10] Throughout 1959 Pierce and AT&T developed plans for a communications satellite experiment. AT&T officials perceived the need to develop strong ground stations first, and AT&T and the Jet Propulsion Laboratory (JPL) each committed to building one. Beyond that, AT&T was committed to developing the transmitters and receivers necessary for active satellites. Throughout this process, AT&T was prepared to go it alone without government investment. The only help required, according to Pierce, was launch capability: an inherently government technology under the control of NASA and the Department of Defense (DoD). By the end of the year, Pierce wrote, “our thoughts were directed toward a simple, low-altitude *active* satellite as the next step.”[11]

Hughes Aircraft Company Enters the Satellite Communications Competition

The 1959 article by Pierce and Kompfner quickly gained the attention of others. At Hughes Aircraft Company, a cadre of engineers under the leadership of Harold A. Rosen saw promise in the idea of a communications satellite and convinced corporate leaders to bankroll their research. Rosen believed that miniaturization of instruments could be achieved in the near term and based his thinking on a lightweight concept that could be launched on a NASA Scout rocket to geostationary orbit. Rosen’s superior at Hughes, S. G. Lutz, realized that whether or not the first lightweight satellite proved anything more than a transitory phenomenon, it would garner prestige for his company. Accordingly, he approved a $5 million budget to pursue the satellite. Lutz knew that the DoD was prepared to spend much more than that on viable satellite communications and was convinced that Hughes could steal the march on other companies, among them AT&T, in the sweepstakes to win contracts for satellite telecommunications.[12]

Lutz formed a Hughes task force to chart a path forward on this initiative. This group reported that communications satellites would be technically feasible, within range of the Hughes budget proposed, and could create an economic climate attractive to further private-sector investment. Hughes corporation officials embraced this strategy, and set about lining up potential business partners and government support. Among those entities Hughes contacted, officials at NASA agreed to support the launch of the Hughes satellite once completed in return for an interest in patent licenses.[13]

Meantime, Hughes engineers pursued satellite design efforts and by the end of 1959 had been successful in scoping out the major features of what became the Syncom satellite, launched in 1963. Among the key technologies pursued at Hughes were spin stabilization, electronics miniaturization, solar collectors, a unique bus structure, and a nitrogen gas propulsion system that made the spacecraft simpler and more robust.[14]

T. Keith Glennan and the Pursuit of Satellite Telecommunications Policy

The efforts of AT&T, Hughes, and other companies to develop and deploy communications satellites set up a public policy debate that had to be dealt with as the space age began.[15] This brings to the fore the issue of satellite telecommunications and the role of the US government in helping to bring it about, facilitate it, and regulate it from the 1960s to the present. Congress set the path forward on this by holding hearings on March 3–4, 1959, about "satellites for world communication." Six witnesses represented the perspectives of NASA, the DoD's Advanced Research Projects Agency (ARPA), AT&T, and International Telephone and Telegraph (ITT). Not surprisingly, the government agencies focused on their technology development and policy priorities, while the commercial entities emphasized the possibilities they foresaw for American business in leading this effort. In sum, it became clear through this hearing that satellite communications were a near-term reality and that the policy and regulatory environment needed to be addressed. There was no room for dithering, all agreed.[16]

This hearing set the stage for AT&T's effort to extend its telecommunications monopoly into space by gaining approval to build its own communications satellites and operate as an approved monopoly. The Eisenhower Administration was warm to this approach. This may be documented in the discussions between NASA and AT&T leaders in the last two years of Eisenhower's presidency. This issue emerges as a source of some frustration in the diary of T. Keith Glennan, NASA Administrator between 1958 and the end of the Eisenhower Administration on January 20, 1961. He alluded to the difficulties of formulating public policy relating to the "economic, political and social implications of space research" on May 9, 1960. He had several issues in mind, but one of them was the emerging communications satellite issue.[17]

On July 27, 1960, just after returning from the trip to NASA's High Space Flight Research Center in the Mojave Desert to review the U-2 and X-15 programs, Glennan met with Eisenhower's Science Advisor, George Kistiakowsky, to discuss "the problems involved in the communications and meteorological satellite areas." The White House was concerned that it was "lagging in the development of public policy" concerning communications satellites, "and that the program could proceed at a very much faster pace." Glennan opined:

> None of it is very reassuring and it is clear that we will have to put some one person in charge of this particular activity. I am reminded, at this point, that no single communication satellite has flown, as yet. The pressures generated by AT&T and by the military as well as by other industrial suppliers are building up quite a fire, however.[18]

The next day Glennan picked this issue up with other NASA leaders. He confided in his diary on July 28:

> It does seem probable that we should ask the president to assign to us the task of developing the basic public policy to be proposed to Congress by the administration. This is the way these things are done; if some one agency doesn't step up and seek the assignment, everyone is apt to rush in and a chaotic condition can prevail. It seems clear to me that it is our responsibility and one that we should not duck. Accordingly, I asked Bob [Nunn] to come up with an outline of a paper to be presented to the cabinet at an early date. This paper would request that the president assign, by executive order or otherwise, the task of developing policy to NASA.[19]

Glennan began to push his staff to develop a position on communications satellite policy that he intended to put before the President, with the intention of leading the development of policy in this new arena.[20]

Glennan constantly referred to this issue as "the communications satellite problem." Indeed, it was more of a problem than an opportunity according to Glennan, because of pressure to act from AT&T, Hughes, ITT, and various military organizations. By the middle of August 1960, just as Project Echo was on the verge of success, Glennan had decided that NASA was the only government body that could take the lead in the communications satellite issue, admitting that NASA had to step up to "owning the problem."[21] On August 11, Glennan reported on a meeting that he had with AT&T:

> We spent almost two hours discussing both public and operating policy questions and finished up with an agreement that AT&T would provide us with an informal statement of its proposed course of action. If, indeed, the AT&T is willing to support research in this field, it is not clear that the government should do more than a minimum. On the other hand, I doubt that AT&T realizes how costly this research will be. In any event, this project must go forward and it is my task to see that it does.[22]

By the end of September, Glennan had taken several meetings with AT&T corporate leaders. He learned that the company was prepared to commit $30 million to the development of a communications satellite, but wanted NASA's support in technology development, launch capability, and some operational activities. As Glennan remarked in his diary on September 15: AT&T

> will spend a great deal more than this if success attends their early efforts. This is the first real break in getting support from an industrial organization using its own funds. The Bell Laboratories have been doing this in a small way in connection with Project Echo, but this move brings new life into the communications picture.[23]

Several of Glennan's advisors believed that NASA support was inappropriate, however, especially since other companies such as Hughes were seeking similar arrangements. Why support one company rather than the other, they asked? It was a valid question. Glennan commented on August 16:

> This was another day! The morning was given over to presentations by the Hughes people and by the Bell Telephone Laboratory people on an "active" communications satellite. There is real pressure on the part of industry to get into this business, and it is reasonably clear that the AT&T is serious about driving toward a communications system using satellites. I asked our people to develop a program for the next three or four years that would involve participation by both of the organizations we have been talking with.[24]

This was especially true because at the same time Hughes was lobbying the White House for NASA funding to develop a communications satellite. Rather than something of a partnership as envisioned by AT&T with both parties putting in resources, Hughes was interested in a government contract that would pay them for the work. Glennan reported in his diary on August 12 that "Leonard Hall, Nixon's campaign manager, had brought to the attention of General Persons the desire of Hughes Aircraft Company for some of NASA's money." While interested in what Hughes was doing, the only reason Glennan could see for supporting the effort was to find "some valid reason for undertaking these excursions to bring political pressure to bear or else the activity would not be undertaken."[25]

The result of this work by Hughes became the Syncom 1 communications satellite, something underway since 1958. Hughes eventually received NASA support for its efforts, largely for the purpose of obtaining experience in using such satellites in synchronous orbit. Syncom 1 was launched on February 14, 1963. It achieved orbit, but communications with the satellite lasted only 20 seconds. Syncom 2 and Syncom 3, launched on July 26, 1963, and August 19, 1964, were successful; thereafter, NASA transferred the Syncom program to the DoD.[26]

Rock-ribbed Republican that he was, Glennan believed that whatever American business could accomplish, American business should accomplish. He was enthused by AT&T's approach to moving out on communications satellites with a minimum of government involvement. He was nonplussed by Hughes' desire to have a NASA contract to do what to his mind was the same work. Glennan believed that supporting AT&T was an appropriate approach: "AT&T is going to be in the business and if we are going to take leadership in getting this program off the ground, it seems to me that we have to take a positive rather than a negative viewpoint in manners of this kind."[27] He noted in a speech at Portland, Oregon, on October 10:

> I pointed out that communications had always been an operation for private industry in this country and I saw no reason for changing that in the event satellites became part of the system. I proposed that the government provide launch vehicles and launching services at cost to those companies, such as AT&T, willing to pursue their own development and pay the costs.[28]

Regardless of his overall support for AT&T, sometimes Glennan was irritated by corporate actions and how they affected NASA efforts. On October 27, 1960, he expressed misgivings about the publicity that AT&T sought for the launch of its satellite, and asked its leaders to keep NASA more center stage in their advertising. Most particularly, Glennan did not want the public to be misled that this was an entirely private activity. He recommended the signing of a cooperative agreement spelling out NASA/AT&T interactions in what would become the first public/private partnership negotiated by the space agency.[29]

Glennan also found the perspective of some of his senior advisors at NASA at odds with his own. Abe Silverstein, NASA's director of space flight programs, for example, engaged in a heated exchange with Glennan over allowing AT&T to extend its monopoly into space. As Glennan characterized it:

> Abe believes that private industry should not have a free hand in the communications satellite business. It is interesting to see the extent to which those people who have spent all of their life in government are negative in their attitude toward industry. I finally had to tell Abe that I was delighted to have his technical judgments but that he would have to leave some of the policy matters to me. I was a little bit tired today, came home rather early and went immediately to bed.[30]

More than this, Glennan noted that some at NASA did not understand what he was trying to accomplish. "There seems to be great fear—perhaps well founded—that we will be accused of avoiding competition," he wrote. "I think we can set up a program where competition will exist but where those who want to take the risk—in this instance, AT&T—will be given a real chance to move forward."[31] At the same time, Glennan sought to mitigate the aggressive manner in which AT&T was pursuing its business case. He told the company's leadership on December 7 that "it is not in the company's best interests to appear as a very large organization attempting to monopolize the communications satellite field."[32]

Glennan reflected the perceptions of the Eisenhower Administration on this matter. In a meeting with Gen. Wilton Persons, Eisenhower's chief of staff, on December 9, Glennan learned that the President wished to make a major statement on communications satellite policy before he left office in January, announcing "his support of ownership and operation by a private organization—probably the telephone company."[33] Calling it "Communications for Peace," Glennan crafted a position paper on the satellite communication issue for the President and presented it to the cabinet on December 19. He explicitly argued "for a statement to the effect that the communications satellite business should be developed as a private enterprise operation." The cabinet approved this statement. Glennan recalled that "I have counted this as one of the significant accomplishments I was able to make in trying to move the communications satellite business forward."[34]

With this decision, Glennan believed that his role in the development of communications satellite policy was completed. He turned the effort over to Robert G. Nunn, who was not a political appointee and would remain in the new Kennedy Administration, for further development. Nunn ran into difficulties, however, at the Department of Justice. The US Attorney General, William P. Rogers, who was still in the job over the Christmas holidays, questioned any approach that favored "AT&T as the 'chosen instrument' of the United States." Rogers emphasized that the US government must ensure that it takes no action to give any one company primacy over another in satellite communications. Additionally, he noted that "the Executive Branch probably should obtain at least the acquiescence of Congress."

Notwithstanding this, Eisenhower issued the NASA position paper at the end of December, emphasizing "that private enterprise should undertake the ultimate development and operation of any non-military communications satellite system."[35] Indeed, the Eisenhower statement may have been more forceful than even Glennan proposed. The President said on January 1, 1960:

> This nation has traditionally followed a policy of conducting international telephone, telegraph and other communications services through private enterprise subject to Governmental licensing and regulation. We have achieved communications facilities second to none among the nations of the world. Accordingly, the Government should aggressively encourage private enterprise in the establishment and operation of satellite relays for revenue-producing purposes.[36]

He specifically directed NASA to "advance the needed research and development and to encourage private industry to apply its resources toward the earliest practicable utilization of space technology for commercial civil communications requirements." Some at the time viewed this public statement as a means whereby the exiting Eisenhower Administration could establish its policy priorities in advance of John F. Kennedy's inauguration.[37]

Yet this issue was far from decided. In the last two weeks of the Eisenhower Administration, Glennan tried to nail down a policy on communications satellites that ensured NASA primacy in technology development and vectored commercial firms in a direction that would be acceptable to those with different perspectives on the policy issues. He commented on this in his diary on January 12, 1961:

> We have reached the point of proceeding with the request for bids for the satellite itself. Competition is the watchword, and once again, patiently, I went over my strong beliefs in this matter. [Leonard] Jaffe and [Abe] Silverstein seem determined that anything short of having someone other than AT&T win the competition will be tantamount to following a

> "chosen instrument" policy. Pointing out that any company might choose to bid $0 or $1 million [and that under those circumstances] a ceiling with the company bearing costs over the $1 million seemed to me well within competitive rules unless otherwise specified in the request for proposals, I gained agreement that we would have to consider such proposals as fair—so long, of course, as the subject company provided a fully documented cost estimate for the total job, etc.

At another point Glennan stated that he kept "hacking away at the prejudice against competitive enterprise and Abe continues to worry about our ability to justify turning over to one company the responsibility for significant parts of the system." Glennan concluded: "Finally, I approved the preliminary development plan and effectively, I guess, washed my hands of the program since nothing will happen before I depart."[38]

Kennedy and the Redefinition of Policy

The wariness that Abe Silverstein articulated regarding communications satellite policy found full expression in the new Administration of John F. Kennedy. While Eisenhower's pro–free market appointees believed then and since that the federal government's intervention in this arena was heavy-handed and in some instances punitive, the New Frontiersmen of Kennedy's Washington felt quite differently. Taking a much more activist approach toward the role of government in American life, in essence they embraced the idea of the "positive liberal state" offered to the world by the USA.

That position celebrated the use of state power for public good. Space activities, they argued, were reasonable and forward-looking and led to "good" results for all concerned. Without perhaps seeking to do so, they advocated for government activism that has raged over the proper place of state power since the beginning of the USA. As only one example of how this has played out over time, in the early nineteenth century the Whig Party sought an activist government that would accomplish important tasks for the benefit of all. Historian Daniel Walker Howe has eloquently called the Whigs the champions of "the positive liberal state." He wrote:

> This ideal implied the belief that the state should actively seek "to promote the general welfare, raise the level of opportunity for all men, and

> aid all individuals to develop their full potentialities." The Democrats, by contrast, believed in a "negative liberal state," which left men free to pursue their own definition of happiness. A great advantage of this distinction between the parties is that it implies a connection between the economic and moral aspects of Whiggery. In both cases, the Whigs believed in asserting active control. They wanted "improvements," both economic and moral, and they did not believe in leaving others alone.[39]

Like the Whigs, the Kennedy Administration believed in activist government. As such, it went beyond bald-faced partisanship: it demonstrated a forthrightness to meet challenges head-on. There are many examples of this, but we see it most starkly in the government activism of the Administration. As David Halberstam shrewdly observed: "if there was anything that bound the men, their followers, and their subordinates together, it was the belief that sheer intelligence and rationality could answer and solve anything."[40]

This translated into an ever-increasing commitment to the use of the government to achieve "good ends," and the war on poverty, the Peace Corps, support for civil rights, the Great Society programs of Lyndon Johnson, and a host of other initiatives are examples. These all represented a broadening of government power for what most perceived as positive purposes. The Kennedy Administration was thrilled with the prospect of creating a new paradigm in satellite communications. With a clean slate, virtually anything is possible, and its members realized that they had the ability to avoid the mistakes of the past.[41]

Immediately after Kennedy's inauguration, the new Administration removed NASA from most of the satellite communications policy negotiations and empowered the Federal Communications Commission (FCC) to reach a policy consensus. AT&T had previously petitioned for permission to launch a communications satellite as an experiment, but JFK's lieutenants questioned this and scrambled to implement a new regulatory environment, something that antagonized AT&T.[42] Members of Congress weighed in as well. Representative Chet Holifield (D-CA) used the free enterprise argument to counter the AT&T position, stating that America should oppose its plan "to operate as monopolies under state control."[43]

In this situation, the White House directed NASA to pursue contracts to aid in developing this new technology. The result was that in 1961 it awarded contracts to RCA and Hughes Aircraft to build experimental communications satellites, the satellites that became Relay and Syncom.

This approach meant that the AT&T lead in satellite communications technology could be mitigated through government.[44]

By 1964, two AT&T Telstars, but also communications satellites built by other firms under NASA contract, had operated successfully in space. Without question, through this set of actions the Kennedy Administration ensured that technological capabilities developed at NASA moved to a range of firms that could challenge AT&T's capabilities.[45]

The Telstar Publicity Harvest

In the midst of this policy discussion, on July 10, 1962, NASA launched AT&T's first communications satellite, Telstar 1 (Fig. 3.2), on a cost-reimbursable basis for the rocket. Appropriately enough, the first Telstar transmission was a panning shot of the American flag waving as "The Star-Spangled Banner" played in the background. AT&T, of course, emphasized Telstar's success as "a tribute to the American free enterprise system" and that by "spending millions of dollars of its own money, the Bell System is exploring new voiceways in space to help bring better communications to the nation and the world."[46]

This was an experiment to be sure, but one with broad implications. AT&T had designed "the simplest experiment that would answer the really critical questions, leaving until a later round of design the optimization of trade-offs and the development and construction of a commercial operating system."[47] The objectives for Telstar included:

1. Testing of basic technologies with a view to looking for the unexpected
2. Demonstrating transmission of two-way telephone, television, data, and facsimile between Earth and space and back
3. Building and operating large ground stations and how to broadcast and receive transmissions
4. Learning the effects of radiation captured in the Van Allen Radiation Belts on transmissions
5. Enhancing the reliability and lifecycle of space systems[48]

Telstar pioneered several technologies that proved critical to future communications satellites, including a traveling wave tube amplifier, solid-state electronics, and component miniaturization.[49]

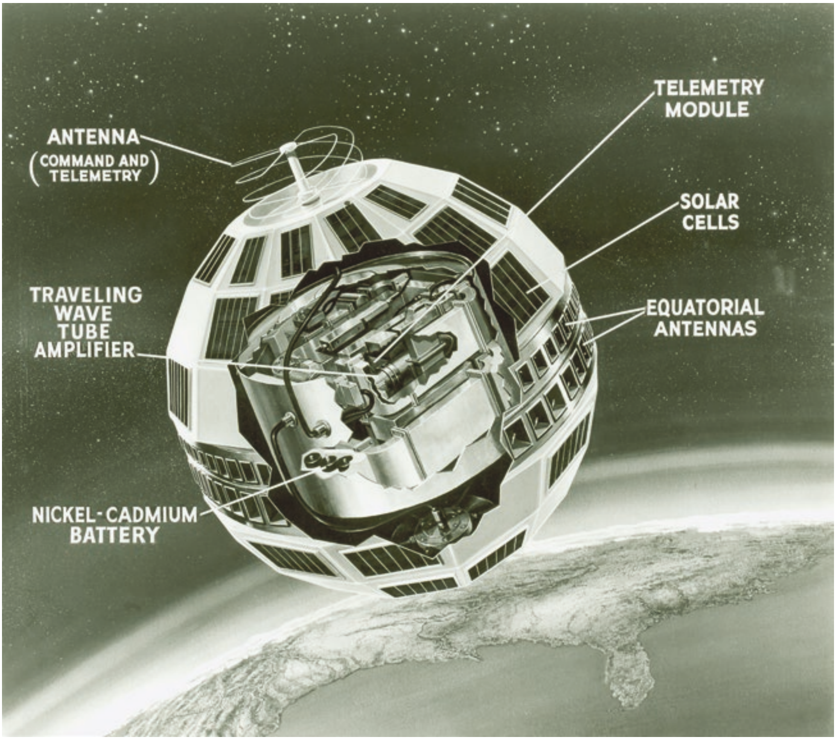


Fig. 3.2 Launched on July 10, 1962, Telstar 1, developed by AT&T, tested basic features of communications via space. Soon after launch, Telstar enabled the first transatlantic television transmission, linking the USA and France. This cutaway drawing of Telstar was released by NASA at the time of the launch. (NASA, image number 62–991, public domain.)

Telstar provided not just AT&T but also the entire USA with a stunning technical success. Its propaganda value worldwide was even greater than Sputnik had been in 1957, according to a United States Information Agency (USIA) poll conducted soon after its launch. This was largely due to the belief that it was much more than a stunt: it represented the dawning of a new age of global instantaneous telecommunications. And while it had been a private venture, the Kennedy Administration's very public efforts to advance satellite communications allowed the nation to garner the lion's share of the stature that Telstar engendered. Indeed, Kennedy hailed Telstar as "our American communications satellite" and "this outstanding symbol of America's space achievements."[50]

After initial tests of the system, on July 23, 1963, a transatlantic gala began with a split-screen image of the Eiffel Tower and the Statue of Liberty, and thereafter an excited chant of "Go, America, Go." A projection of idealized national concepts followed for days thereafter, especially from prime users in the USA, the UK, and France. It showed presidents and prime ministers, athletes and actors, and sporting events and popular entertainment. Even Pope John XXIII got in on the act with a broadcast from Vatican City to pilgrims with a message of strengthening "brotherhood among peoples" and said that this "marked a new stage of peaceful progress." Historian Arnold Toynbee promised that this new capability offered "new hope for the survival of the human race" against the threats of nuclear annihilation, because it was "the nearest thing to meeting physically face-to-face."[51] Not surprisingly, by the fall of 1962 the British instrumental pop group The Tornados had released a song named for the satellite and it climbed the charts in both Europe and the USA, eventually reaching number 1.

Telstar became the best-known telecommunications satellite of all time and, according to NASA official Leonard Jaffee, "is probably considered by most observers to have ushered in the era of satellite communications."[52] AT&T followed the success of its initial Telstar with a second satellite, Telstar 2, launched on May 6, 1963. Telstar's publicity served its creators well, but it did not portend AT&T's having control of satellite communications thereafter, largely because of legislative actions creating a public/private partnership for satellite communications.[53]

The Satellite Communications Act of 1962 and the Communications Satellite Corporation

At the same time and largely for similar policy reasons, the Kennedy Administration sponsored the Communications Satellite Act of 1962. Kennedy had talked in his 1961 State of the Union Address about the need for cooperative ventures with other nations in developing satellite communications systems, and explicitly called for aggressive efforts to create a new communications satellite network in his "Urgent National Needs" speech on May 25, 1961.[54] To facilitate this effort, NASA and the FCC agreed to divide responsibilities, with the FCC handling spectrum allocation and policy implementation and NASA overseeing technology development.[55]

In June 1961, Kennedy directed the National Space Council to develop a way forward for communications satellite policy. The Space Council reviewed actions to date, considered joint-venture arrangements, applauded NASA's decision on patent policy that gave the government royalty-free use of AT&T patents and licensing rights, and recommended its extension over other agreements and contracts. The Kennedy Administration's Davenport study, commissioned by Kennedy science advisor Jerome Wiesner, factored into this, because it reported that all of the communications satellite programs, regardless of which company was pursuing them, were technically appropriate and politically useful.[56]

Congress also got in on the act, lighting a fire of expediency to legislation that might follow, seeking "to determine the extent that private industry should participate in the space communication program, and … to create a further sense of urgency among all involved in this important program." The approach of the Kennedy Administration in communications satellite policy was succinctly stated by NASA administrator James E. Webb in congressional hearings in the summer of 1961:

> We, in NASA, look to the FCC to take proper action on the problem of organizing the resources of private industry in such a manner as to meet governmental requirements and conform to public policy. On the other hand, we, in NASA, have the job of developing the space technology which any private organization authorized by the FCC will be able to utilize to provide communications services to the public.[57]

By the end of July 1961, Kennedy had decided to press for legislation to create a public/private partnership, part owned by the government and operated by a government-chartered corporation. The government would retain responsibility for regulation, foreign negotiations, R&D, and launching with operations in the private sector.[58] The Space Council drafted the initial legislation emanating from the White House. It called for a government-chartered corporation with broad ownership and limited authority. It placed limitations on the number of shares any single entity could own; it also mandated foreign participation up to and including ownership of shares and of ground stations. This assumed maximum efficiency in most people's minds, while government involvement ensured that it would have the public's good as a major objective.[59]

By early 1962, three bills had been introduced to the Senate, each reflecting the public versus private primacy issues held by their sponsors. First, a bill (S2650, 1/11/1962) authored by Robert S. Kerr (D-OK) favored ownership by the carriers in an approach not unlike that championed in the Eisenhower Administration. A second bill, the Kennedy Administration's effort (S2814, 1/27/1962), favored a public/private partnership; a third bill by Estes Kefauver (D-TN) (S2890, 2/26/1962) advocated government ownership. Not surprisingly, the second bill effectively surrounded AT&T and kept it both from going it alone and from dominating the market for European satellite telecommunications.[60] The House of Representatives acted first, passing on May 3, by 354 to 9, an Administration-supported bill. The Senate then enacted this bill on August 17 with a vote of 66 to 11. On August 31, 1962, President Kennedy signed it into law.[61]

This law created the Communications Satellite Corporation (COMSAT), with ownership divided 50/50 between the general public and the various telecommunications corporations. It was incorporated in the District of Columbia on February 1, 1963, with Leo D. Welch of Standard Oil Co. (New Jersey) becoming chairman of the board and Joseph V. Charyk, former Under Secretary of the Air Force, serving as president of the organization.[62] They set about organizing the corporation, acquiring $5 million in capital borrowed for start-up, and began initiatives for the first satellites and ground stations operated by the corporation.[63]

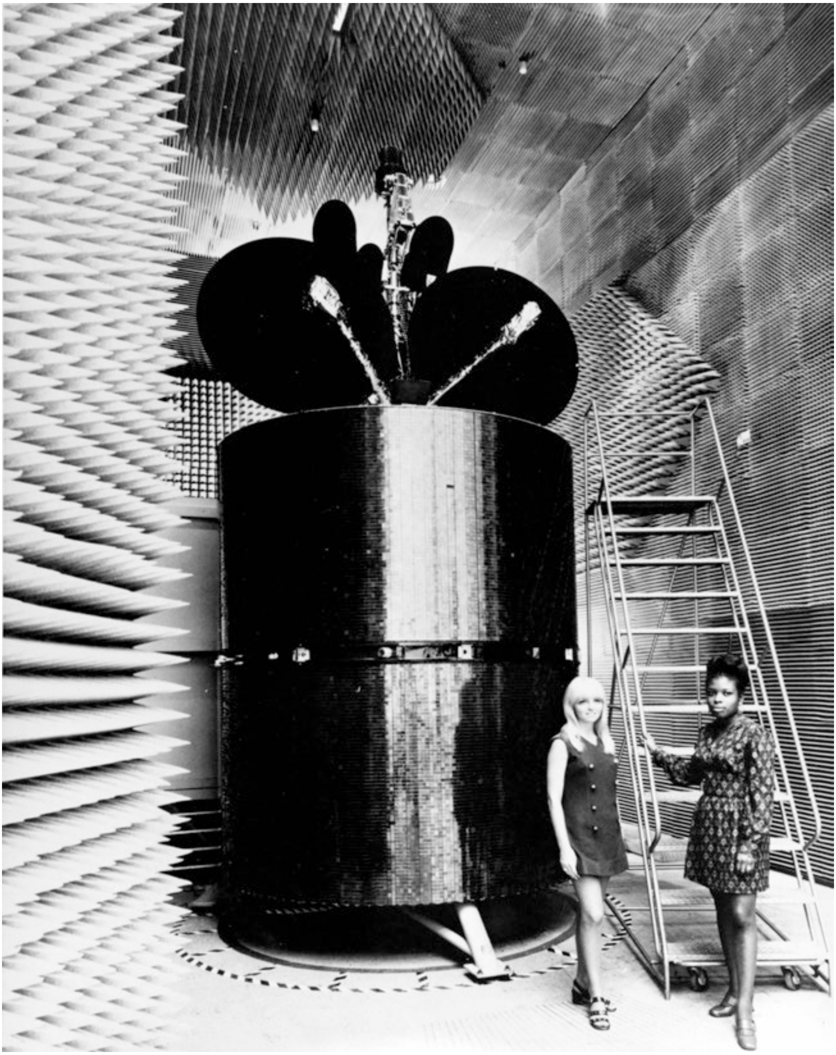
Creation of this company proved a boon to virtually all entities involved in the matter, except for AT&T. John Pierce commented: "The Communications Satellite Act discouraged me profoundly. At that time it seemed to end any direct personal interest of participation in satellite communications. It foresaw that the Act would, as it did, considerably delay the realization of a commercial satellite system."[64] His personal disappointment was nothing in comparison to corporate chagrin: the law effectively took AT&T out of the running for domination of new technologies for satellite telecommunications, and prompted a retrenchment of AT&T investments in undersea cables.[65]

Within its first year, COMSAT had awarded contracts to AT&T, RCA, and Hughes to study the technology necessary for Earth stations. It also undertook contracts for the development of geosynchronous satellites, which became the Early Bird series, first launched in 1965, that would bridge the gap between experimental and operational status.[66]

Later, COMSAT became the American manager of an emerging global system known as the International Telecommunications Satellite (Intelsat) consortium, formed on August 20, 1964. Founded by 19 nations, with eventual membership of well over 100, it was initially very much an American organization, with the USA controlling 61 percent of the voting authority and all of the technology. On April 6, 1965, COMSAT's first satellite, Early Bird, was launched from Cape Canaveral. Global satellite communications had begun.[67] From a few hundred telephone circuits in 1965, the Intelsat system rapidly grew to become a massive organization providing millions of telephone circuits. And the costs persistently declined, making the backers of this technology appear geniuses. Whereas customers had paid as much as $10 per minute using older, cable-based technology, the new satellites reduced costs to less than $1 per minute.[68]

Even before this time, government officials realized they had a "winner" on their hands. In 1964, NASA administrator James E. Webb asked his staff, "How did we get so much communication satellite technology for so little money?"[69] His question was not satisfactorily answered by his NASA lieutenants, but space commerce has been dominated by satellite communications and Webb and his successors have ballyhooed it ever since. Within a few years, the number of telephone circuits increased from 500 to thousands and live television coverage of events anywhere in the world became commonplace.[70] The sale of all components associated with satellite communications—development, launch, and operations—surpassed $100 billion a year in the first part of the twenty-first century (Fig. 3.3).

Although the initial launch vehicles and satellites were American, other countries had been involved from the beginning. By the time Early Bird was launched, the UK, France, Germany, Italy, Brazil, and Japan had established communications ground stations. From modest beginnings and a handful of members in 1965, the Intelsat system grew to embrace more members than the United Nations and to offer technical capabilities unmatched elsewhere. Cost to carriers per circuit, and to individual customers, declined dramatically as the system matured. By the end of the twentieth century, orbiting satellites were generating billions of dollars annually in sales of products and services and had transformed global communication by facilitating commercial broadcasting, business and scientific exchanges, and telephone and Internet communication among individuals worldwide.[71]



◀ **Fig. 3.3** An image, taken on July 5, 1972, depicts in an advertisement the Intelsat IV communications satellite in an anechoic (sound-absorbing) chamber, along with two female employees. The satellite stood over 17 feet tall, with an average of 6000 voice-grade circuits. Hughes Aircraft Company built this satellite, and it was operated by the Intelsat consortium of 65 nations, of which COMSAT was the American member. This consortium had been established on August 20, 1964, to satisfy the growing demand for greatly expanded international communications. The Intelsat IV was placed in a synchronous orbit over the Atlantic with a capacity of about 6000 circuits or 13 television channels in 1972. (NASA, image number 72-H-872, public domain. Available at https://www.nasa.gov/multimedia/imagegallery/image_feature_527.html)

NASA and the Continued Advance of Communications Satellites

Largely frozen out of the policy debate—with only an advisory role to the FCC—NASA played to its strengths and undertook technology development for communications satellites. Beginning in 1962, it started work on Syncom, a second-generation geosynchronous communications satellite that followed the first Syncom satellites.[72] These satellites, according to engineers who studied the program, "demonstrated the feasibility of placing a satellite in geosynchronous orbit and maintaining precise stationkeeping and orbital control."[73]

In 1964, NASA widened its geosynchronous satellite concept into the multi-dimensional Applications Technology Satellite (ATS) program. ATS would consolidate multiple experiments into a single program, focus on technology development for geosynchronous orbit, and explore various spacecraft stabilization techniques. As it turned out, NASA contracted with Hughes to build five ATS satellites altogether, two with a spin-stabilized configuration and three that were gravity gradient stabilized, with various other systems tested on a common structure. NASA launched the first, ATS-1, on December 7, 1966, and it undertook not only a variety of communications experiments but also collected weather data. A notable outcome was that ATS-1 transmitted the first full-disk Earth image from geosynchronous orbit. The satellite also lasted quite a long time: its communications system functioned until 1985. Three additional satellites—ATS-2 failed to reach orbit—tested other concepts for communications satellites.

ATS-3 was notable for its longevity. Launched in November 1967, this satellite operated for more than 28 years. A notable success was that when Mt. St. Helens erupted on May 18, 1980, this satellite tracked tons of volcanic ash that spread eastward, allowing meteorologists both to warn of danger and to study the effects of the explosion on the world's climate. The last two satellites operated for less time, but enabled the advance of gravity-gradient spacecraft. The experiment determined whether or not a difference in the gradients between the top and the bottom of the spacecraft was strong enough to stabilize it at geosynchronous orbit without significant fuel expenditure. These satellites were technical failures, although later gravity-gradient spacecraft did prove successful.[74]

Several companies interested in satellite communications chided NASA for undertaking the ATS program. They fundamentally believed that the space agency had overstepped its mandate in contracting with Hughes to work on the program. NASA succinctly stated its rationale for this decision: "Mr. [James E.] Webb, Dr. [Hugh L.] Dryden, and Dr. [Robert C.] Seamans concluded that, despite the serious consideration of exempting this procurement from competition, the government could maximize its chances of getting the best performance, schedule, and cost results on the ATS project by selecting Hughes at this time."[75] Both then and since, criticism of this decision has been periodically offered, but NASA got away with this approach for the ATS program.[76]

A second, related concern was NASA's involvement in what private-sector firms believed should be a commercial effort. Leaders of COMSAT, of course, believed keenly that NASA was directly competing with their efforts. NASA probably crossed what may have been a fine line at various points, but it sought to hew to communications satellite R&D rather than operational activities. While the ATS program may be considered a success as a technology demonstrator, the perceived constant incursion into commercial activities forced NASA to terminate its efforts. As President Richard M. Nixon sought to decrease NASA's budget in the early 1970s, this type of work became an easy target for termination. Lauding NASA's efforts to create communications satellite capabilities, a NASA press release in 1973 announced: "Further advances in satellite communications research and development can be accomplished by industry on a commercial basis without government support."[77] Many doubted that American firms would pick up the slack, and they were right. Accordingly, in President Jimmy Carter's Administration in the later 1970s, NASA returned to communications satellite R&D.[78]

The Advanced Communications Technology Satellite (ACTS) resulted from that decision. As a follow-on program to ATS, this effort explored communications satellite technology in new transmission bands that offered more sophisticated television capabilities. The industry knew that Ku-band would be critical for video distribution to a broad set of users and for the emerging direct-to-home broadcasting. This succession of satellites had numerous successes. One analysis of the program concluded that it fostered a "revolution in satellite system architecture by using digital communications techniques employing key technologies such as a fast hopping multibeam antenna, an on-board baseband processor, a wide-band microwave switch matrix, adaptive rain fade compensation, and the use of 900 MHz transponders operating at Ka-band frequencies."[79]

Regardless, the program remained controversial despite its emphasis on support to the commercial sector, much more in the mode of National Advisory Committee for Aeronautics R&D before World War II. In sum, this program concentrated on technology development in the mid- to long-term arena; technology that could be freely adopted for commercial purposes by private firms. Where NASA received criticism, it seemed, was over whether or not ACTS should involve flight testing of satellites. Two denunciations dominated: (1) NASA's contractor building flight hardware would receive unfair competitive advantages in future efforts; and (2) the belief that NASA was incapable—indeed, the entire federal government was incapable—of guiding system development usable by commercial entities.[80]

Indicative of the first criticism, Hughes Space and Communications Co. chairman Steven D. Dorfman cautioned NASA to stay with subsystems R&D rather than full testing of satellites. Doing otherwise, he believed, would create an "undesirable distortion" in the competitive relationship between satellite manufacturers.[81] The second criticism was more philosophical. There had been enough instances in the nation's history of the government pursing "white elephants" that no one wanted to warrant caution. Journalist William J. Broad summarized this position: "federal officials lack the knowledge to predict what technologies will succeed in the marketplace and are never canny with taxpayer money, unlike entrepreneurs who risk their own."[82] The program proceeded regardless and stalwart supporters crowed by the latter part of the 1990s that NASA's ACTS program had proven technologies that were then being adopted by the satellite industry, thus demonstrating the wisdom of undertaking the effort.[83]

An Emphasis on Lessons

Perhaps the core issue to be considered in the history of space-based global telecommunications is whether or not this is more of a government activity or a commercial one. While AT&T developed the first communications satellite, the US government launched it on a reconditioned military missile. While AT&T sought an open system for business, the government moved to regulate and control it as a public good, not unlike public utilities. International space telecommunications followed a similar close relationship between government and industry. Accordingly, should satellite communications be viewed as a public trust or a free-market arena? How should such activities, whatever the specific industry, be administered?[84]

This is a large question in American history, economics, and society. Additionally, the manner in which space enterprises are stimulated—investment, business models, returns on investment, and the like—has been a uniquely important topic for some time, but few have looked at how historical case studies might inform future efforts to stimulate space commerce. The story of COMSAT is a case study of how government and the private sector undertook the development of what became a remarkably lucrative space business. The need to sustain that industry into the twenty-first century prompted the Clinton Administration in 1993 to pursue public/private partnerships for a range of other space enterprises (Fig. 3.4).[85]

With the rise of a range of private-sector entrepreneurial firms interested in pursuing space commerce since the beginning of the twenty-first century, the process whereby those might be incubated, fostered, and expanded has come to the fore as an important public policy concern as never before in the history of the space age.

Over the years, several lessons have emerged from these efforts. First, NASA is a less than effective organization in the definition of policy. It played a subservient role in every aspect of the politics of communications satellite policy. Appropriately, elected officials had responsibility for defining the nature of satellite services and how they would be provided, while such organizations as NASA implemented the policies. Of course, the agency's officials had their own beliefs about the best strategy, but in most cases they toed the line of the administration they served.

Second, the NASA effort worked best when it was conducted within the confines of a public/private partnership. That partnership emerged

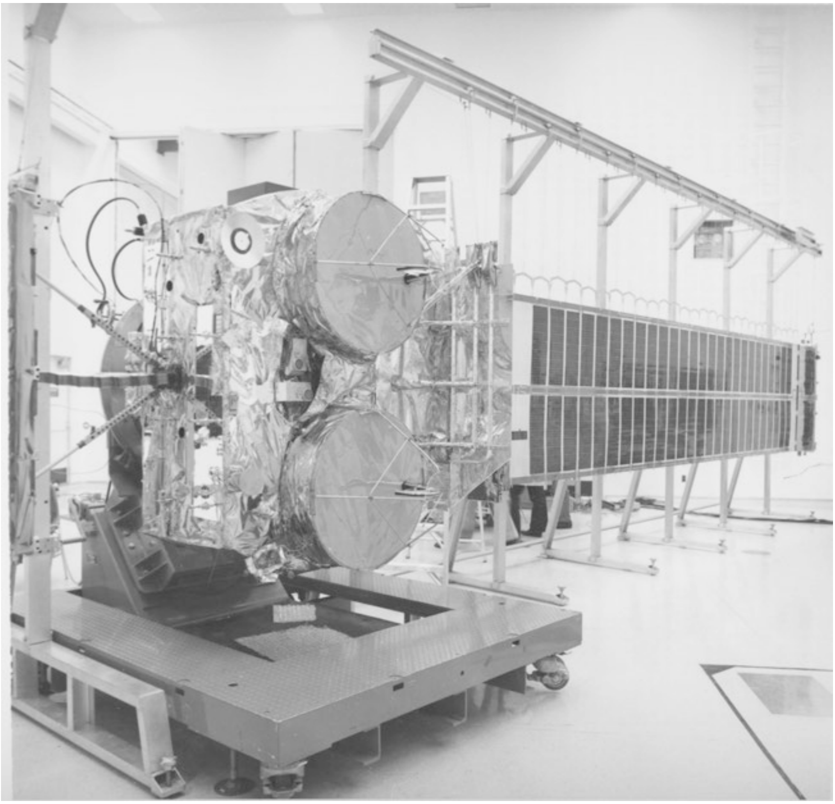


Fig. 3.4 This experimental communications technology satellite was launched on January 17, 1976; it operated until October 1979. A joint NASA/Canadian effort, Hermes had much more transmitting power than previous satellites, making it possible to use smaller ground stations and thereby paving the way for direct broadcast television. This was the second satellite designed to transmit high-quality color television. The first was the Application Technology Satellite (ATS), which was launched on December 17, 1966. (NASA, image number 75-H-1112, public domain. Available at https://www.flickr.com/photos/44494372@N05/16502401602)

in an uneasy manner during the 1960s, with NASA engaging in R&D and the 50/50 public/private COMSAT engaged in delivering operational services. Over time, NASA moved from the emphasis on short- and mid-term results to long-term R&D that could be translated into economic gain only a decade or more after the flight experiments. This ensured that no one company received undue benefit from working with NASA on the flight hardware.

Finally, in the current environment any expansive space program will require a practical, cost-effective, commercial basis. Leveraging a declining public investment for this agenda with public/private partnerships, as was done in the satellite communications arena on a more equitable basis, is the most obvious methodology for achieving an expansive future in space. While one can question an emerging neoliberal perspective that argues that government support of scientific research is counterproductive to wealth-generating technology, and that private enterprise can supply most if not all of the funds required for both pure and applied research, there is still no doubt that less funding will be available for this endeavor in the future than in the past.[86]

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CHAPTER 4

The Other Side of Moore's Law: The Apollo Guidance Computer, the Integrated Circuit, and the Microelectronics Revolution, 1962–1975

Paul E. Ceruzzi

Fly Me to the Moon[1]

It was NASA's end item spec.
That triggered a world of high tech.
They simply asked for the moon.
And they wanted it soon.
So we gave them their moon trek.
—Jayne Partridge Hanley.
MIT Instrumentation Laboratory.
Used by permission.
July 1994.

Looking back from the perspective of the early twenty-first century, it seems unreal that between 1969 and 1972, 12 American astronauts

Reprinted from Eldon C. Hall, *Journey to the Moon: The History of the Apollo Guidance Computer* (Reston, VA: AIAA Press1996), xix. Used by permission.

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walked on the Moon's surface and returned home safely, fulfilling a challenge set by President John F. Kennedy, made when the USA had a total of 15 minutes' experience of putting a human being into near space. We marvel at the technological advances that NASA and its contractors seemed to produce on an almost daily basis during those years. Just to mention a few:

1. The choice of the Lunar Orbit Rendezvous method of reaching the Moon, a technique that saved the expense and time of a larger or second Saturn launch vehicle, but that required mastery of a complex piece of orbital mechanics almost a quarter of a million miles away from Earth.
2. The development of liquid hydrogen fuels for the upper stages of the Saturn rocket: theoretically highly efficient, but mastery of which was full of unknowns.
3. The development of a spacesuit—in effect a miniature spaceship that had to keep astronauts alive while also allowing them to maneuver and work on the lunar surface.
4. The Apollo Guidance Computer, a device that performed the never-before-combined operations of navigation, guidance, and control of the Apollo spacecraft and the Lunar Lander by digital means. At the time of its design, most computers occupied large, climate-controlled rooms and were programmed by punched cards.

This chapter explores a key aspect of that last breakthrough: the decision by the designers of the Apollo Guidance Computer to use the newly invented silicon integrated circuit as its basic electronic component. Related to that decision is the belief, widely held and hinted at in the poem by MIT employee Jayne Hanley quoted above, that the decision was the "trigger" for the whole silicon chip revolution in microelectronics that followed from the 1960s to the present day. One may be skeptical of so bold a claim, but we know there was a close relationship between the needs of military and aerospace electronics customers and the commercial electronics industry.[2] What was the relationship between NASA and the innovative culture of "Silicon Valley"? Was it only a coincidence that space exploration and microelectronics both proceeded at a fast pace during the 1960s?

During that decade, Silicon Valley was known only by the names of the towns, in Santa Clara County, where the microelectronics industry was concentrated. The invention in 1959 of the planar process for making transistors, and later integrated circuits, at Fairchild Semiconductor in Mountain View, set the pace. The public knows of that pace by the phrase "Moore's Law," the result of a 1965 paper on integrated circuits by Fairchild employee Gordon Moore. That decade corresponds perfectly to a decade of fast-paced innovations in the American space program, progressing from a 14 kg Explorer and 1.5 kg Vanguard satellite, both orbited in 1958, to humans walking on the Moon between 1969 and 1972.

The story of the development, programming, and operation of the Apollo Guidance Computer, and of how it helped meet President Kennedy's challenge, has emerged as a focus of accounts of both computing and aerospace history.[3] It offers an opportunity to cut through what the late Professor Michael Mahoney called the "trackless jungle" of circuits, computers, components, software, and applications that has made writing the history of computing after 1945 so refractory.[4] The story of the Apollo Guidance Computer's design, construction, and use is complex, but not overwhelmingly so. Its critical role in one of the most dramatic events in twentieth-century technology gives it a public appeal that, say, accounts of business data processing lack, however important that also was.

The dramatic role of the Apollo Guidance Computer has led to a distorted view of its history, which this case study will attempt to rectify. When on July 16, 1969, a Saturn V rocket launched astronauts Neil Armstrong, Edwin "Buzz" Aldrin, and Michael Collins on a path to the Moon, they were assisted by not one but four digital computers, two of which were Apollo Guidance Computers. The other two embodied a different philosophy of design and construction. At Mission Control in Houston, TX, the mission was assisted by a suite of IBM System 360/75 mainframes, among the most powerful mainframe computers then available. And on the final Apollo mission, an Earth-orbit rendezvous with a Soviet Soyuz capsule in 1975, the crew carried a *fifth* computer, again with a unique design and construction.[5] The different designs reflect not only a vigorous debate among engineers as to the best way to build reliable, powerful, and compact digital devices on which human lives depended. They also give us a window into the pace of components technology—a look at the finer structure of innovation behind the phrase "Moore's Law."

The Launch Vehicle Digital Computer: The First of the Five Apollo Computers

If the technical breakthroughs listed above seem obvious and brilliant in retrospect, they were hardly considered so at the time. The skepticism regarding the Lunar Orbit Rendezvous decision, for example, and how it even involved President Kennedy, has been well documented.[6] The decisions regarding the Apollo Guidance Computer were also controversial. The 1961 NASA contract with the Instrumentation Laboratory for the Apollo guidance and navigation system was one of the first contracts signed at the onset of the Apollo program. Independently of that effort, engineers at the Marshall Spaceflight Center in Huntsville, AL, were working on a succession of ever more powerful launch vehicles, culminating in the Saturn V. Going back to a time when the engineers at Huntsville were part of the US Army's Redstone Arsenal, they had established a strong relationship with IBM Corporation for the critical launch vehicle guidance components.[7] For the Saturn 1B and Saturn V rockets, IBM's Federal Systems Division supplied an instrument unit, mounted above the upper stage of each, on which the various guidance components were mounted. A launch vehicle digital computer (LVDC), built by IBM, performed critical guidance and navigation functions.

In contrast to the Apollo Guidance Computer, however, the control of the Saturn V rocket engines—sending commands to the engines to direct their thrust—was handled by a separate *analog* computer, also mounted in the instrument unit and supplied by Electronic Communications, Inc., of St. Petersburg, FL.[8] This was a reflection of the more conservative approach to missile guidance at Huntsville, going back to the V-2 rocket of World War II. As historian David Mindell argues, the June 1964 decision to combine guidance, navigation, and control into one, all-digital device for the Apollo command module was one of the most radical steps taken by Massachusetts Institute of Technology (MIT), equal to the bold step of choosing integrated circuits.[9]

The LVDC did not use integrated circuits. At the time of its design, IBM was well aware of the invention of the planar process at Fairchild, and its engineers were facing a decision that would affect the very survival of IBM in the coming decade. IBM was one of the largest customers in the USA for transistors and other discrete computer components; it was also a major manufacturer of solid-state devices. The rest of the US electronics and computer industries felt a need to keep one eye on IBM to see what the company was up to—a practice that made it difficult to compete with IBM head to head in mainframe computers. It also gave components suppliers a reason to worry that their choice of circuit design was destined to fail if IBM chose another avenue, or, worse, that IBM would adopt their choice and use its clout to drive them out of business.[10]

In August 1961, a few short months after Robert Noyce of Fairchild was granted a patent for the planar integrated circuit, IBM issued an internal report describing the need for miniaturized components for its new line of computers, eventually announced in 1964 as the System/360 family of mainframes.[11] Shortly before the announcement, another internal report argued that "monolithic circuits" (IBM's term for what is now known as the integrated circuit) did not pose a competitive threat to the company. By that time IBM had developed its own method of miniaturization, which consisted of mounting transistors and other components on a ceramic substrate. That method, called solid logic technology (SLT), was chosen for the System/360, and the devices were produced in huge quantities for the remainder of the decade.

For the LVDC, IBM used a more compact version of that device, which the company called a unit logic device or ULD.[12] However, by the end of the decade IBM had recognized that the integrated circuit (IC) was the superior technology, and built its follow-on mainframe, the System/370, using monolithics. The System/360 was a huge commercial success for IBM, which had "bet the company" on its introduction. We have already seen that NASA chose a suite of them for Mission Control in Houston, where they replaced older IBM 7094 mainframes. It is hard to argue that its decision to use SLT was wrong, but IBM's transition to ICs for the System/370 a few short years later had a depressing effect on the company's profits (Table 4.1).[13]

The designers of the LVDC addressed the reliability issue by having the computer's major circuits produced in threes, with a voting circuit to select the majority if one failed. IBM called this "triple modular redundancy," and in some early accounts of the dispute between IBM and MIT the computer is called the "TMR Computer."[14] IBM felt that it was necessary to ensure reliability for a computer that was subject to the high accelerations, temperature extremes, and vibration modes that the Saturn experienced during launch. For all of the flights of the Saturn 1B and Saturn V, the computers worked perfectly. That included the

Table 4.1 The various names of microelectronics, ca. 1960–1965

Cordwood	Control Data Corporation, other manufacturers	Not an integrated circuit but a way of packing discrete circuits densely, like a stack of firewood
Micrologic	Fairchild	Planar process, using silicon, photo-etching. Ancestor of modern chips
Solid circuits	Texas Instruments	Early designs used "flying wires"
Integrated circuit	Signetics	Term also used at Fairchild, but the latter preferred micrologic. Has since become the common name
Monolithics	IBM	Similar to Fairchild; used on System/370 and subsequent IBM computers after 1970
Solid logic technology	IBM	Discrete devices mounted on ceramic substrate; used for System/360 computers, beginning in 1964
Molecular electronics	US Air Force/Westinghouse	Described as integration at molecular level; never precisely defined or successful
Unit logic device	IBM	Used by IBM on the launch vehicle digital computer; similar to solid logic technology
Micromodule	US Army/RCA	Similar to IBM's solid logic technology
Thin film	Sperry UNIVAC, other computer companies	No single technique; depositing of circuit elements on an insulating substrate

flight of Apollo 12, in November 1969, when the Saturn V was struck by lightning just after launch. That caused most of the electrical systems in the command module to cycle off, but the LVDC continued to guide and control the Saturn V without any problems. The launch proceeded smoothly and the mission went on to be a complete success.

Early in the Apollo program, NASA contracted with AT&T to provide technical and managerial assistance for select technical issues. AT&T in turn established Bellcomm, an entity that carried out these analyses. In late 1962, Bellcomm recommended that IBM, not MIT, supply the computers for the Apollo command and lunar modules. The arguments were complex and contentious, and even reached members of the House of Representatives.[15] In a letter to NASA Administrator James Webb, Representative Joseph E. Karth (D-Minnesota) listed a number of questions. Among them were these:

> 2. There has always been apprehension about the MIT guidance system achieving the required reliability to ensure a safe mission. Is there documented test-proven data to show that it will meet the needs of APOLLO/LEM?
>
> 3. In regard to the previous question, is there a back-up guidance function of sufficient breadth and proven development that can allow the APOLLO/LEM mission to attain success … in the event of catastrophic failure of the MIT guidance?[16]
>
> …
>
> 7. Is a backup system still contemplated for either APOLLO or LEM?

The letter listed five other questions, but of all the issues raised, these stood out. Was the MIT system reliable?

The Apollo Guidance Computers on the Command and Lunar Modules: The Second and Third Computers

The MIT Instrumentation Laboratory resisted the Bellcomm suggestion. Because the command and lunar modules were carrying human crews, the environment inside them was not as harsh as that of the Saturn V instrument unit. The launch vehicle computer had a specific and narrow task, albeit a complex one, while the Apollo Guidance Computer had to have a more general capability. It had to be programmable by the human crew as well as accepting inputs from telemetry and other on-board systems over the span of a long journey. The greater computational needs were enough to sway NASA away from the Bellcomm critique, after a vigorous defense from the Instrumentation Laboratory engineers. In response to the seventh question from Representative Karth, however, NASA did specify a backup device on the lunar module: the Abort Guidance System, the fourth of the five computers mentioned at the beginning of this chapter.

At the early stages of design there was a plan to fit the command module with two identical Apollo Guidance Computers, but at the recommendation of a NASA engineer in Houston, that plan was dropped.[17] The command and lunar modules each carried an identical Apollo

Guidance Computer, with changes in software tailored to the specifics of each module. For the command module, the crew themselves would serve as a back-up, executing commands sent up from Houston, derived from the System/360 mainframes at the Johnson Spaceflight Center. (That capability was proven during the Apollo 13 mission.) Otherwise, the Apollo Guidance Computer had none of the redundancy of the LVDC and embodied a philosophy of reliability quite different from that used on the Saturn V. The MIT engineers argued for a different approach: rather than design circuits that would detect and compensate for errors, MIT decided to design enough reliability to be confident that there would be *no* failures.[18] The resulting computer would be simpler: no redundant logic modules, no voting circuits, and no "disagreement detectors" to record when a module failed.

Reliability and the Electronics Industry, ca. 1960

"Put all your eggs in one basket—AND WATCH THAT BASKET!"

Mark Twain, *Pudd'nhead Wilson's Calendar* (1894), Chapter 15.

Before discussing the decision to use ICs in the Apollo Guidance Computer, it is necessary to place that decision in the context of the fast-evolving use of electronics in military and civilian aerospace applications, and how military demands for reliability, small size and weight, and low power consumption differed from civilian uses of similar devices. Two novel features of the Apollo guidance and navigation system have already been mentioned: the choice of integrated circuits for the computer, and the decision to make the system all digital. To them we add a third: the decision by MIT to make the computer as reliable as possible and have no back-up. That decision goes to the heart of the suggestion to use the IBM LVDC design for the command and lunar modules. From its origins in the work of Thomas Edison through to the 1950s, electronic equipment was centered around a component that was fragile, unreliable, bulky, and power hungry: the vacuum tube. Unlike most other components in an electronic device, the tubes were mounted in sockets, so that they could be replaced when necessary—which was often. There were heroic exceptions: the famous Proximity Fuze that was one of the Allies' secret weapons of World War II used subminiature tubes that were able to withstand the shock and acceleration of being fired from a gun.[19] When the point-contact germanium transistor was invented in the late 1940s, it was heralded as eliminating all of the above drawbacks, especially the reliability problem. When first applied to complex circuits, however, the transistor came with its own set of problems. By the 1950s vacuum tubes were being mass produced in great quantities, with predictable characteristics, known reliability statistics, and at low cost. By contrast, transistors were notoriously difficult to produce. The early "point-contact" design required placement of leads at close tolerances, which manufacturers had difficulty achieving. In many cases, one did not know how much gain (amplification) a transistor could deliver until *after* it came off the assembly line and was tested. Reliability was not good either: transistors made of germanium had a limited temperature range, and they often failed when subject to shock and vibration.

Most readers are familiar with the famous graph that accompanied Gordon Moore's 1965 editorial on "Cramming More Components on to Integrated Circuits"[20] (Fig. 4.1). For this chapter, we will look at

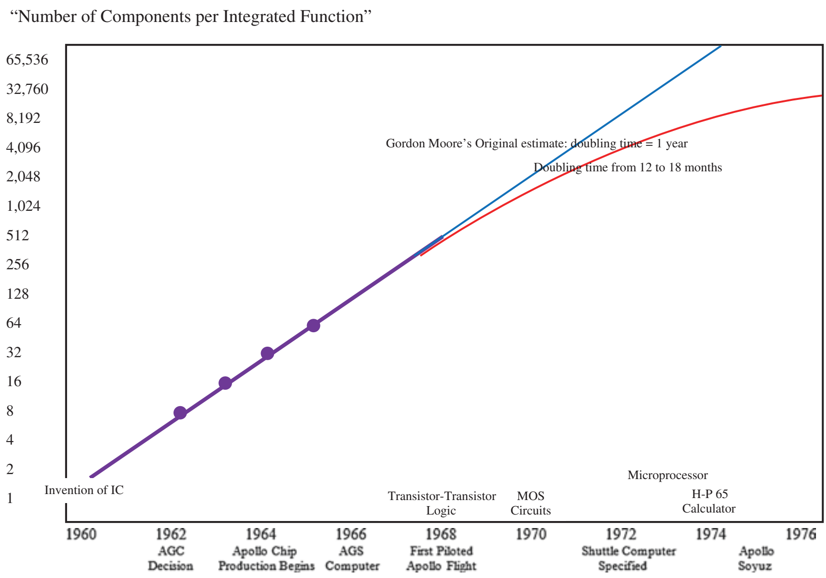

Fig. 4.1 Moore's Law, in the context of the Apollo missions. Compiled by the author from various sources and from Gordon Moore's original graph, *Electronics* (19 April 1965), p. 116

a more nuanced version of that graph, drawn by H. G. Rudenberg of Arthur D. Little a few years later[21] (Fig. 4.2).

The bold, middle line in Fig. 4.2 represents the number of circuits integrated on a single chip. The first thing to notice is that between 1948 and 1959 the slope of this line is zero: the complexity of circuits remained constant; there was no “doubling time.” This is the side of Moore’s Law that is seldom discussed. The dashed line to the left of the solid line, labeled “laboratory progress,” tells us why. Although not based on actual figures, the dashed line represents the enormous amount of materials and solid-state physics research that was going on between 1947 and 1959. That was laying the foundation for the exponential growth that began with the invention of the IC, and has continued on ever since.

The number of basic innovations that made the IC possible are numerous, and they have been well documented.[22] Two of them stand out, one occurring relatively early in the 1950s, the other at the end. The first was the development in 1954, at Bell Laboratories and later Texas Instruments, of the ability to make transistors out of silicon, in

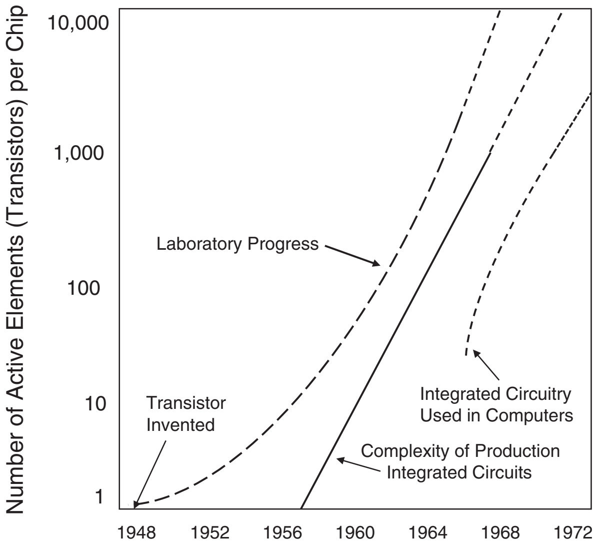

Fig. 4.2 From H. G. Rudenberg & C. G. Thornton (1969), p. 362 (© AFIPS, used by permission.)

place of germanium. The second was the development of the planar process for making transistors. The latter innovation was accomplished in 1959, at Fairchild Semiconductor in Mountain View, CA. As the dashed line on the graph suggests, the research component of chip manufacture preceded the construction of chips by a decade at first, and remained always a few years ahead thereafter.

The Planar Process and the Invention of the Integrated Circuit

Accounts of the growth of Silicon Valley cite the invention of the planar process as the key to the ever-increasing density of silicon chips. However, it is also the key to the issue most pressing for NASA, namely the reliability of electronic circuits. Its invention has been attributed to Jean Hoerni, a Swiss-born chemist who worked at the Shockley Semiconductor Laboratory and was among the "traitorous eight" employees who left Shockley to form Fairchild Semiconductor in 1957.[23] He was also among the first of the "Fairchildren"—employees who left Fairchild to form other companies in and around Santa Clara County, creating the culture of what would later be called Silicon Valley.[24] In 1958 Fairchild was a small company located in Mountain View, and its main product was the high-speed silicon transistor, in which layers of materials were built up on a silicon base using photographic techniques. The layers of materials resembled the mesas of the American southwest, with variously colored layers of sandstone jutting up from the plains. "Mesa" transistors worked well, but their geometry made them fragile. Hoerni's insight was to leave a layer of silicon oxide on the circuit, not removing it as others had done, and then to remove select sections later on by photographic etching.[25] This made the transistor at once more rugged and resistant to damage; it also had the effect of electrically isolating the underlying transistor. The planar process made possible the transition from a single transistor on a chip to an IC containing transistors, resistors, and diodes on a chip, eventually in the hundreds of millions. Moore's Law was born. And Fairchild Semiconductor catapulted itself into being the world leader in semiconductor electronics.

The planar process allowed Fairchild Semiconductor to turn the whole reliability issue upside down. It justified MIT's decision to use ICs in the Apollo Guidance Computer, and to drop the redundancy techniques that IBM employed in its Saturn LVDC. It also eliminated the need, which had been suggested for earlier Apollo Guidance Computer designs, to have spare modules on board, so that astronauts could replace a defective module with a spare should the computer fail in flight.[26] During the fall of 1964, as the "Block II" Apollo Guidance Computer was taking form, the decision was made to forgo in-flight maintenance and repair.

Apollo program manager Joe Shea summarized this shift in philosophy concisely, stating in an engineer's terms what Mark Twain had observed decades before: "systems designed for in-flight maintenance will justify that decision by inherently requiring more maintenance." By the early 1960s the reliability of electronic devices was becoming evident, while the disadvantages of in-flight maintenance were creating further problems of weight, volume, and thermal control.[27] A major turning point was the flight of Mercury-Atlas 9, piloted by Gordon Cooper in May 1963. Several critical electrical systems failed near the end of the mission, and Cooper had to reenter the atmosphere by manual control. It was later determined that acidic fluids, floating in the zero-g environment of the capsule, penetrated small openings in the electronic devices, and in an oxygen-rich environment the fluids corroded the electronics more readily than when the devices were tested on the ground. [28]

Thus, the MIT Instrumentation Laboratory proceeded on the assumption that the computer would not fail. The astronauts would carry no spare parts or tools to make repairs. The computer would be "potted" to keep out contaminants, and it would be inaccessible to the crew during a flight.

The High-Reliability Program

Well before Fairchild's involvement, the electronics industry was adapting to the needs of military aerospace. The concept of designing equipment to be serviced periodically had to be scrapped. Not only vacuum tubes, but electrolytic capacitors and variable resistors and capacitors, which were common in both consumer and ground-based military equipment, were suspect. So too were mechanical relays. Electronic equipment was an increasing part of the expense of new-generation aircraft and missiles. However, as US Air Force Major General Bernard A. Schriever noted, "A number of American missile failures can be traced to faulty small 'nickel and dime' components." Along with weight, power consumption, and volume for aerospace requirements, reliability was first among equals.[29]

Schriever had been appointed head of the Western Development Division of the Air Force's Air Research and Development Command in 1954, and was charged with developing an intercontinental ballistic missile (ICBM) to counter a perceived lead by the Soviet Union in booster technology. The Air Force's first ICBM, Atlas, was liquid fueled and took a long time to be readied for launch, rendering it of limited value against a possible Soviet attack. The Titan, a liquid-fueled follow-on to Atlas, was marginally better, but the real breakthrough came at the end of the decade, when advances in solid fuel rocket technology, warhead design, and inertial guidance led to the Minuteman, a solid-fueled rocket that could be kept in silos and ready for launch on short notice.[30]

In 1958, the Autonetics division of North American Aviation was selected as an associate prime contractor responsible for the Minuteman's guidance system and associated electronics. Minuteman production proceeded in the following years through 1977. The one-time deployment of about 1000 missiles has since been reduced to about 450, which remain on alert, 24 hours a day, in silos across the western USA. In its selection of Autonetics, the Air Force stressed the need for reliability that was at least two orders of magnitude greater than existing military electronics systems. The missiles had to remain on constant alert, yet ready to fire less than 60 seconds after a command is given. While in the silo, the Minuteman computer was tasked with day-to-day monitoring of the missile's systems, a task that was performed by an external computer for the Titan. That meant that it would not have to be suddenly switched on prior to a launch, but also that it would have to run reliably around the clock. The warheads had a much smaller yield than the Titans that they were to replace; the Minuteman compensated for that by its constant readiness, and by having greater accuracy. Thus the guidance system had not only to be more accurate, it had to maintain that accuracy with no degradation while in the silo.[31]

To achieve the necessary reliability, Autonetics borrowed techniques pioneered by Bell Telephone Laboratories for the design of undersea telephone cables. From Bell came the notion of documenting the history of every electronic component, who handled it, what was done to it and when, what tests were performed on it and when, and what "lot" a particular component belonged to (i.e., what other similar components were produced at the same time from the same production run). Certain types of components, such as potentiometers and vacuum tubes, were expressly forbidden. Those that were selected were "derated," or designed to operate at power levels lower than they were designed for. Assembly was to be done in strictly regulated “clean room facilities.”[32]

For the Minuteman I guidance system, Autonetics decided that the mesa-type silicon transistor was to be used wherever possible.[33] Fairchild was among the suppliers that were hoping to sell transistors to Autonetics, and in preparing its offer it adopted the stringent reliability demands needed to qualify. The much larger Dallas, TX firm Texas Instruments (TI) also met those requirements, and TI would go on to become the main supplier of components to the Minuteman program.

Fairchild, at the time a small start-up company, regarded the stringent requirements for Autonetics as crucial to their success as a supplier of transistors, and later of ICs. After MIT chose the IC for its Apollo Guidance Computer, the MIT Instrumentation Laboratory adopted similar techniques.[34] At its plant in Mountain View, Fairchild instituted a testing program that went far beyond what then was common. Transistors were mounted in a centrifuge and spun up to high g-forces. They were tested at extremes of temperature, hot and cold. Packaging was designed to protect the circuits once delivered. Borrowing from the aerospace field, the silicon devices were bonded to a nickel-cobalt alloy, Kovar, which had the property of having the same coefficient of thermal expansion as borosilicate glass, thus preventing the circuits from cracking as they underwent temperature changes.[35] Roomfuls of women peered into binocular microscopes to check the connections and integrity of the devices. Most histories of Fairchild and its spin-off companies focus on the eight men who founded it and the men who left to found other semiconductor companies in Silicon Valley; in the mid-1960s, however, two-thirds of the company’s workforce were women.[36] Photographs show the women wearing smocks; full-coverage gowns and face masks came later.

These Minuteman “Hi-Rel” techniques, imposed by Autonetics, were initiated to improve the reliability of discrete silicon transistors. The techniques carried over to the IC era with few modifications. One change was that after a wafer was processed but before it was diced, women skillfully guided a set of tiny pins onto each chip, to determine whether it was a good circuit or not. If it was not, she would dab a spot of ink on it, and it would be rejected. The percentage of good chips on a wafer, called the “yield,” was one of the most critical metrics in the industry (and remains so today). The result of this approach to reliability played a crucial role in getting NASA to accept the use of chips in spacecraft. Once a chip passed these tests, NASA could be assured that the device would not fail in use. Period. That eliminated the need for cumbersome "belt and suspenders" redundancy, or the need for astronauts to carry diagnostic instruments, tools, and spare parts to make repairs in cislunar space.

Texas Instruments

Around mid-1962, work began on an improved Minuteman, later dubbed the Minuteman II. The second-generation missile was to have greater accuracy, greater range, and, above all, was to be quickly retargeted if necessary. That placed demands on the guidance computer, which led in turn to the selection of integrated circuits in its design. The primary supplier was Texas Instruments. Westinghouse was a second source, together with TI delivering 15,000 circuits to Autonetics per week in the summer of 1965.

In 2000 Jack S. Kilby, retired after a long career at TI, won the Nobel Prize in Physics for his role in inventing the integrated circuit.[37] His career and work are better characterized as engineering, not physics, but there were few if any critics of the Nobel Prize Committee's choice. In his acceptance speech, Kilby acknowledged that had Robert Noyce been alive, he too would have shared the prize (Noyce died in 1990, at the age of 62). The simultaneous invention by Kilby and Noyce has been extensively studied. To summarize, Kilby applied for a patent in February 1959; Noyce, who had been thinking along similar lines when he heard of Kilby's filing, applied for a patent in July. Representatives for the two inventors fought in the courts, but well before a final decision was reached in 1969, they agreed to share credit and to cross-license each other's portfolio of patents relating to the IC.[38] By that time the industry had moved far along: "TI and Fairchild agree that their own bilateral pacts will be unaffected by the Appeals Court ruling."[39] The dispute centered around Kilby's method of interconnection among the various components on the chip: his patent application showed fine wires, presumably attached by hand, to make the connections, while Noyce's drawing showed a flat surface that contained both the devices and their interconnections. Fairchild employees called the TI method "flying wires," which they argued was clearly inferior to their planar design.

With the cross-licensing, TI was able to use the planar process, although for a while it apparently tried to market a chip with devices connected by wires, with little success.[40] By the mid-1960s, it was universally agreed among chip manufacturers that the "flying wire" device was a technological dead-end, but note that chip production at that time still involved roomfuls of women carefully attaching gold wires to the leads of planar ICs. That process was eventually automated, but the high labor costs of the final assembly stages soon drove most chip manufacturing to low-wage Asian countries, where it resides to this day. The credit to Kilby and Noyce, and to no others, must be seen in the context of the hodgepodge of ideas, some practical, some fanciful, addressing the need to miniaturize military and aerospace electronics. [41] The planar IC cut through that tangle.

For the advanced Minuteman II, TI was asked to develop a set of around two dozen different types of ICs to be used in the guidance computer.[42] The computer itself had about 2200 ICs, plus several hundred in other on-board equipment. Kilby recalled how in the early 1960s there was much skepticism among electrical engineers as to the value of this invention. Traditionally an engineer would carefully design a circuit and choose the optimum values of discrete components to carry out its function, balancing cost, reliability, power consumption, and so on to achieve an optimal design. With the IC, this design work was encapsulated inside the "black box" of the package, with design decisions made by the chip manufacturer in advance of any application.

Even Gordon Moore was skeptical at first, fearing that the IC would eat into Fairchild's lucrative business of selling high-performance discrete transistors. He soon changed his mind. The famous 1965 editorial, which gave birth to the law named after him, was his sales pitch to the industry, trying to convince engineers that the chip was here to stay.[43] Kilby recalled making numerous presentations to military brass, in which he compared the performance of the Minuteman I computer with its successor that used ICs: "In the early 1960s these comparisons seemed very dramatic, and probably did more than anything else to establish the acceptability of integrated circuits to the military."[44] The first contracts from Autonetics to TI for the Minuteman II were dated November 1962, about a year after the MIT Instrumentation Laboratory was selected to provide guidance and navigation for Apollo.

The Apollo and Minuteman II programs ran concurrently, together consuming a large fraction of all the ICs then in production. Of the two, the Minuteman program consumed far more, with its deployment of hundreds of missiles in silos. (However, one could argue that more chips flew into space on Apollo than on the Minuteman missiles.) As the suppliers traveled down the "learning curve," increasing the yield per wafer and the overall cost per chip, the costs steadily declined, for example from $18 per chip at the beginning of 1965 to $12 per chip by July.[45] That was also the peak year for hardware development of the Apollo Guidance Computer. Early in the decade, Apollo and Minuteman dominated the sales of chips, but by the time Apollo flights commenced, a large commercial market had developed as well. The first half of 1964 saw a crucial turning point: by the summer of that year industrial (non-government) customers increased their share of total chip sales several-fold. Chip manufacturers had ramped up production and were producing a large quantity of high-reliability devices, yet there was still skepticism among industrial customers as to the advantages of ICs over discrete circuits. In response, the chip suppliers drastically lowered prices, even selling chips at a loss. In doing so, they established the viability of the IC for once and for all.[46]

Minuteman II made its first test flight in September 1964. An unmanned Apollo capsule, containing a "Block I" computer that used first-generation ICs, flew atop a Saturn V in November 1967. Apollo's first piloted flight was in October 1968, and carried a Block II computer that used a more advanced IC. TI continued to flourish as a supplier of circuits through the 1960s to the present day. Fairchild did well through the 1960s, while somehow surviving the departure of half of its founders in 1961 to found rival companies and thus giving birth to Silicon Valley (Table 4.2). The departure of Noyce and Moore in 1968 to form Intel was a serious blow to the company, but that was the nature of economics in the Valley.[47] As engineers departed, they took valuable, tacit knowledge with them. There were threats of lawsuits, but that did not stop the flow. Employees at these companies accepted a rapid turnover and founding of new companies as a fact of life. Don Hoeffler, the chronicler of Silicon Valley and the one who popularized the term, claimed that in at least one instance, employees heard rumors of a defection and covertly bought stock in the rival company, thus becoming wealthy when the news went public. [48] We shall see that this volatility, which drove so much innovation in the Valley, was not compatible with the needs of the aerospace community for more continuity, even in the case of a fast-paced program like Apollo.

Table 4.2 The "Fairchildren" and the birth of Silicon Valley, 1960–1980

Only the first and a select few second-generation spin-offs from Fairchild Semiconductor are shown. Fairchild employees shown in italics.
1947 Invention of transistor at Bell Labs
1955 Shockley Semiconductor Laboratory
1957 Fairchild Semiconductor *(Traitorous Eight: Gordon E. Moore, C. Sheldon Roberts, Eugene Kleiner, Robert N. Noyce, Victor H. Grinich, Julius Blank, Jean A. Hoerni, and Jay T. Last)*
1961 Amelco *(Jean A. Hoerni and Jay T. Last)*
1961 Signetics *(David Allison, David James, Lionel Kattner, and Mark Weissenstern*)
1985 Cirrus Logic
1967 National Semiconductor (preexisted but hired *Charles Sporck* in 1967)
1981 Linear Technology
1983 Sierra Semiconductor
1983 SDA Systems
1967 Intersil *(Jean A. Hoerni)*
1968 Intel (*Gordon E. Moore, Robert N. Noyce)*
1974 Zilog (Federico Faggin)
1981 SEEQ
1968 Computer Microtechnology
1973 Synertek *(Bob Schreiner)*
1969 Four Phase (*Lee Boysel)*
1969 Advanced Micro Devices *(Jerry Sanders)*
1983 Cypress
1972 Kleiner Perkins Caufield & Byers *(Eugene Kleiner)*
1980 LSI Logic *(Wilfred J. Corrigan)*

The Apollo Contract

President Kennedy challenged the nation to send a human being to the Moon in a speech given in May 1961. In August, NASA awarded the MIT Instrumentation Laboratory a contract to supply the guidance system. It was the first major contract for the Apollo program; the first of what would turn out to be a myriad of contracts, ultimately costing in the billions of dollars, with laboratories and aerospace suppliers.[49] The close personal relationship that had developed between NASA Administrator James Webb and Instrumentation Laboratory Director Charles Stark Draper played a role. There were other deciding factors. The lab had established a track record of supplying a guidance system for the Navy's Polaris submarine-launched ballistic missile. And in 1957 it had carried out a study for the Air Force Ballistic Missile Division for the guidance and navigation of an unmanned, 150 kg spacecraft that could fly to Mars, take high-resolution photographs, and return the film to Earth. From this study came the notion of using a sextant to take periodic sightings of stars, the Sun and planets, coupled with a compact digital computer to calculate course corrections—concepts carried over to the Apollo mission.[50]

Following this award, most of NASA's contracts for Apollo went to aerospace firms, not to academic laboratories. Yet the Instrumentation Laboratory was unique in many ways. Its expertise in inertial guidance was widely acknowledged as one of the greatest. In the early discussions about how to get to the Moon and back, guidance and navigation, not computing, were of primary concern. Many of the employees of the other suppliers of inertial guidance systems had been students of "Doc" Draper at MIT. Draper had established strong relationships with industrial firms, including the Sperry Gyroscope Corporation of New York and the AC Spark Plug Division of General Motors. A few months after getting the Apollo contract, the Instrumentation Laboratory enlisted the support of the Raytheon Corporation, which built the computers in its suburban plant outside Boston. The AC Spark Plug Division of General Motors, located in Milwaukee, WI, supplied the inertial measurement unit.[51] In this regard, the Instrumentation Laboratory functioned in a manner similar to the way NASA's Marshall Space Flight Center managed contracts with the several aerospace corporations that built the engines and stages of the Saturn V rocket, as directed by Marshall engineers.

The lab had already established a relationship with TI for devices used in the Polaris guidance system. TI delivered sample ICs in 1962 for possible use in Apollo. ICs were new and untested, but not entirely so. There is some disagreement among historians as to when the first ICs flew in space, but it is known that the Orbiting Solar Observatory, launched in March 1962, carried ICs supplied by TI for evaluation; that is, a failure of the IC technology would not jeopardize the mission.[52] TI supplied these first chips in space, but Fairchild discrete transistors were also extensively used in spacecraft by that time as well. By 1962 Fairchild was marketing a family of from six to nine ICs, which the company advertised would be suitable as building blocks for a general-purpose digital computer.[53] The elegance of Fairchild's planar technology, plus its emphasis on component reliability, led MIT to consider its products.

Historian A. Michal McMahon argued that the choice of Fairchild chips for the Apollo Guidance Computer was due in part to the close personal involvement of Robert Noyce in the negotiations with Eldon Hall of MIT. Noyce was also an alumnus of MIT and may have been more comfortable with the academic culture of the Instrumentation Laboratory. In late 1962, NASA, on Hall's recommendation, decided to use ICs for the computer, and to use Fairchild's design.[54]

The reliability issue was not settled by this decision, however. Recall that TI developed a set of around 20 types of ICs for the Minuteman II. Fairchild was offering a set of from six to nine ICs that performed the basic functions of computer logic, arithmetic, and processing—a smaller number, but sufficient to build a high-performance general-purpose computer. The Apollo Guidance Computer would use only *one* of them: a three-input NOR gate.

Students of computer science learn early in their course work that all the functions of a computer processor can be built up from a single device of sufficient complexity, including a three-input NOR gate. In practice, that is seldom done. Why use several of these logic gates to form, say, an adding circuit when Fairchild was offering a single chip to do just that? The answer was reliability. The designers of the Apollo Guidance Computer were following Pudd'nhead Wilson's dictum to keep things as simple as possible, and paid close attention to the circuit they chose to use. In the words of Eldon Hall:

> Had a second type of logic microcircuit been employed in the computer, the number of logic elements could have been reduced by about 20 percent. But it is clear that to have done so would have been false economy from the point of view of reliability, for neither of the two circuits would have accumulated sufficient operating history to demonstrate the high mean time between failures with the confidence level of a single NOR circuit.[55]

To further understand the choices faced by the computer's designers, we return to Fig. 4.2, from the 1969 paper by H. G. Rudenberg. We have already noted his observation of the lag between what he called "laboratory progress" and the number of circuits that can be placed on an IC. On the right side of the graph is another dashed line, "integrated circuitry used in computers." That line reveals another time lag: between the introduction of a circuit and its use in a product. Rudenberg argues, as did Eldon Hall, that before one can use a circuit, one has to test it. Especially in the case of aerospace applications, one has to subject the circuit to tests that determine its reliability. Some of these tests can be accelerated, but they do take time. Rudenberg begins that dashed line at about the year 1966; before that he felt that ICs had not proved themselves to be accepted by computer manufacturers. This is in line with IBM's decision not to use the IC for its System/360 line of mainframes (1964), and it reveals again why Gordon Moore wrote his editorial promoting the advantages and bright future of the IC (1965).

The Instrumentation Laboratory chose the Integrated Circuit in 1962. According to Rudenberg's and Gordon Moore's graphs, in that year chips could contain from six to eight devices, which is about the density of the three-input NOR gate. Fairchild had made a strong pitch to demonstrate the reliability of their "Micrologic" devices; to that, the Instrumentation Laboratory added further sets of tests. The Bellcomm report, which favored the triple modular redundancy in the IBM computer, was another reflection of the charge that the selection of the circuit was premature.[56] Grumman, the builder of the lunar module, was also skeptical. During the portion of the mission between the Earth and the Moon, astronauts could (and did) rely on ground-based computers and telemetry to navigate. During the powered descent to the lunar surface, however, the time delay of radio signals and the need for fast, real-time calculations made it imperative that the on-board lunar module computer not fail.

No Apollo Guidance Computers experienced a hardware failure during a mission. What was more, in at least two instances, the computer's robustness saved a landing from a probable abort.[57] Historians of technology argue that there is a lot of "interpretive flexibility" in the design of a complex system such as the Apollo guidance and navigation system.[58] A number of alternative computer configurations could have been used, and they could also have worked. The configuration that was chosen, using the newly invented IC, could have failed, even if the components cost more than a "nickel and dime," in General Schriever's words. That was the lesson of the Apollo 13 mission, when the crew nearly perished due to a short-circuit deep inside one of the service module's oxygen tanks.

The choice of Fairchild Semiconductor, not TI, for the circuit design was fortuitous, with the benefit of hindsight. Fairchild Semiconductor and its numerous spin-off companies were the engine that transformed the region between Palo Alto and San José into Silicon Valley. That story has been extensively studied, especially by residents of other regions of the world who wish to replicate the phenomenon. Christophe Lécuyer and others have shown how the region had deep roots in electronics and military systems long before Robert Noyce and his seven "traitors" left Shockley Semiconductor.[59] Can NASA and the MIT Instrumentation Laboratory claim some of this credit? Yes, for no other reason that their bold decision to go with the IC at such an early phase of its development. The previous discussion also reveals another factor: the Fairchild IC was an evolutionary, not revolutionary, advance beyond the planar transistor that the company invented. It would prove to be revolutionary, as Moore's Law took hold and the circuit density accelerated into the billions. In 1962 that circuit density was small enough that the suppliers were able to package the ICs into the same "TO-5" (Transistor Outline-5) packages—resembling small top hats—that were used to package discrete transistors. The only outward difference was that the package had a few more leads coming out, reflecting the complexity of the IC contained in it.

The Block II Computer and Moore's Law

We return a third and final time to the graph of semiconductor density depicted in Fig. 4.2. From that graph we see that in 1962, when the Apollo Guidance Computer was first taking form, it was possible to place about six devices on a chip. In May 1963, in response to a further understanding of the computational needs for the lunar landing, the early "Block I" design evolved into a "Block II" Apollo Guidance Computer, with more memory and faster execution times for double-precision arithmetic. The number of integrated circuits increased from 4100 to 5600. Volume and weight were reduced, from 1.2 to less than 1 cubic foot of volume and from 87 to 70 lb of weight.[60] Moore's Law and Fig. 4.2 tell us that by mid-1963, the number of circuits on a chip had doubled. Thus, the Block II computer used a chip that contained two three-input NOR gates instead of one (Fig. 4.3). And the ICs were now packaged in a flat housing, with leads coming out of the edges, instead of the bulkier TO-5 cans. As we now experience in consumer electronics, the Block I computer was obsolete before it ever had a chance to guide a human crew (the unmanned Apollo 4 flew in November 1967 with a Block I computer, which functioned without error).[61]

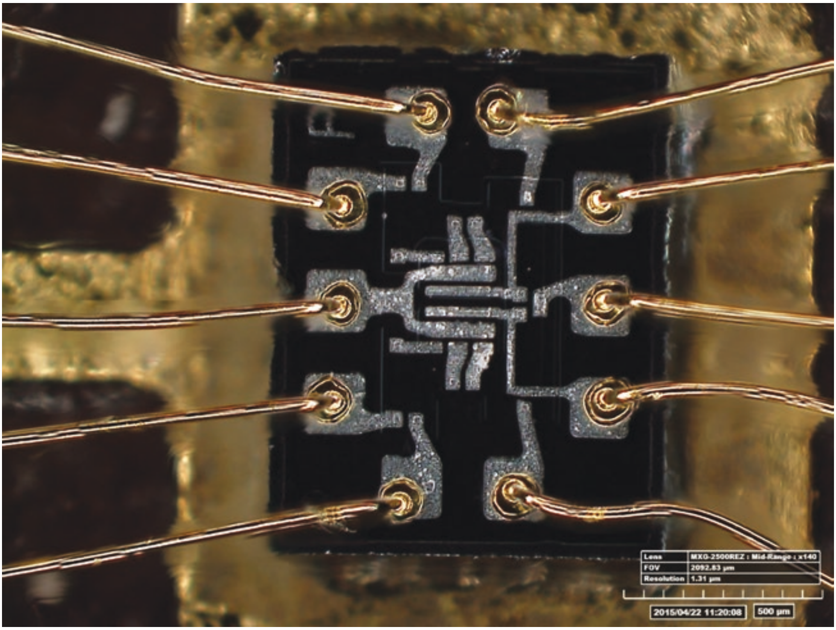

Fig. 4.3 Dual three-input NOR gate, used in the Block II Apollo Guidance Computers and manufactured by Philco (Photo by Lisa Young, Smithsonian National Air and Space Museum, TMS A2017003000.)

The Abort Guidance System: The Fourth Computer

The detailed analysis of the lunar module's requirements in 1963–1964 led to a more sophisticated back-up system—the fourth of the five computers for Apollo. It began as a simple sequencer, whose primary mission was to get the crew safely off the Moon in an emergency. A redefinition of the program in 1964 led to the much more capable Abort Guidance System, a general-purpose computer with its own data entry and display assembly (DEDA) interface for the crew.[62] The computer was built by TRW of Redondo Beach, CA. It had a smaller instruction set and a smaller memory, but a faster cycle time than the Apollo Guidance Computer.[63] TRW also supplied the software. This computer also used ICs. These were supplied not by Fairchild but by Signetics, a Sunnyvale, CA company founded by three employees who left Fairchild in 1961, and who thus were among the first "Fairchildren" in the Valley. (One of the founders, David F. Allison, had worked for William Shockley at Shockley Semiconductor and was employee #10 at Fairchild.)[64]

Signetics was founded with the goal of producing nothing but silicon ICs. It also specialized in a circuit design that had several advantages over the Fairchild products then available. The chips used in the Apollo computer used a form of logic called "direct coupled transistor logic," which combined a set of resistors and transistors to carry out the NOR function. Because of its use of resistors, it was also known as "resistor transistor logic," or RTL. Signetics perfected a way of using not resistors but diodes in the circuit, which resulted in better performance: higher speeds, lower power consumption, and greater noise margins. The Abort Guidance System used these diode transistor logic circuits. TRW considered marketing the system as a commercial computer, called the "MARCO" ("Man-Rated Computer"), but there is no evidence this was done. Thus by getting a late start in the process, the Abort Guidance System was a superior computer, even if it had a more modest design and fewer requirements. And TRW's choice of Signetics chips foreshadowed the day when Fairchild would no longer lead the Valley's semiconductor industry.

The computer was successfully tested during the Apollo 10 mission, but its use as an emergency back-up was never needed. In 1975 a brief analysis of the Apollo guidance and navigation systems concluded that the redefinition and expansion of the capabilities of the Abort Guidance System was not without its drawbacks. In particular, its display/keyboard (DEDA) was not the same as the one used by the Apollo Guidance Computers (DSKY). That meant that the astronauts had to learn two separate sets of keystrokes that essentially carried out the same guidance functions, thus increasing their workload. The report concluded: "Every consideration in future hardware definition should be given to placing redundancy in the primary system rather than incorporating a separate and different backup guidance system."[65] One may read that as an indictment of the MIT approach to reliability, or as a mistrust of MIT by Grumman engineers. This philosophy was carried out, to an extreme, in the space shuttle that followed Apollo.

By the time of the Apollo 8 mission in December 1968, around 400 devices could be "crammed" onto a single IC, in Gordon Moore's term. By that metric the functions of the Apollo Guidance Computer could have been carried out by around 100 instead of the 5600 chips it used.

Of course that was not practical, as the testing and validation process for Apollo or any aerospace application took time. Aerospace computers must always lag behind advances in semiconductors. Their designers cannot follow the practice of designers of modern consumer electronic products such as smartphones. Those who produce consumer products design the product not with the chips that are available today, but with chips that the engineers expect will be available on the day that production begins. The chip manufacturers have no choice but to deliver what they promise. They have been doing that for five decades now, and anyone who claims that Moore's Law is ending has to be willing to be embarrassed when it continues.[66]

By 1968, neither Fairchild nor its spin-offs were interested in marketing or manufacturing chips with six transistors on them. By then Fairchild had mostly abandoned RTL, as did its competitors in the Valley. The chips used in the Apollo Guidance Computer were not made by Fairchild but by the Philco Corporation, at a plant in the suburbs of Philadelphia. After the Apollo 8 mission in December 1968, the Fairchild employee newsletter mentioned how its products were of crucial importance in the Apollo telemetry system. The newsletter did not mention the Apollo Guidance Computer at all. Operating on a fast clock that seems to run only in Silicon Valley, Fairchild had moved on.

Philco's production line was crucial to the success of the Apollo missions, yet the company is hardly discussed in the official histories. Philco supplied thousands of ICs, which had to pass rigorous quality control tests and on which the lives of astronauts depended. It was paid for its work, although we have seen that by 1965 the prices for the chips had dropped to low levels. The contract did little to help Philco's position in the industry. In the early 1960s, it was a world leader in the production of fast transistors. The nascent minicomputer manufacturers located around Boston's Route 128 used these to great advantage as they competed with IBM and the other giants of the computer industry.[67] Beginning in 1953, Robert Noyce had worked for Philco before moving to California to work for Shockley. In 1961, Noyce rebuffed Philco's attempt to obtain a license to produce ICs.[68] Perhaps Noyce was wary of letting his former employer enter the field. The company changed its mind, however: for the Apollo chips, Philco had a cross-licensing agreement to use the Fairchild processes. However, it did not leverage the Apollo contract into a competitive position in the IC industry.

Apollo–Soyuz and the Fifth Computer

After you've run—and won—a race, you stop running. That seems obvious in hindsight, but after the successful early Apollo missions to the Moon, it was difficult to come up with a sensible plan to proceed to the next step in human space exploration. Nevertheless, the long hours, tight deadlines, near disasters during several missions, and enormous costs could not continue. Further missions to the Moon were canceled after Apollo 17. The hardware then being prepared for subsequent missions ended up in museums and NASA visitors' centers. Surplus Saturn–Apollo hardware was used successfully for the Skylab space station in 1973, which three crews of astronauts visited. Finally, in 1975, an Apollo command and service module was joined to a Soviet Soyuz capsule in low-Earth orbit. The crews of the two craft met, shook hands, and exchanged ceremonial gifts, foreshadowing future collaboration in space. The Apollo–Soyuz mission was a one-off, however, and genuine cooperation between the USA and Russia did not occur until years later.

Once again, the critical calculations for rendezvous and docking between the two spacecraft were carried out flawlessly by the on-board Apollo Guidance Computer. And in case anything went wrong, the American crew carried a back-up. In January 1974, the Hewlett-Packard Company (HP) of Palo Alto, CA introduced the HP-65 pocket calculator. In addition to performing basic calculator functions, the device was programmable, storing instructions on magnetic cards the size of a stick of chewing gum. HP advertised the HP-65 as a "personal computer," although purists complained about that designation. Nonetheless, it did have the capability of performing complex trigonometric calculations, and it was programmable. The Apollo–Soyuz astronauts carried one into space, and NASA developed a set of programs for it to perform critical rendezvous and docking calculations, orient the high-gain S-Band antenna, and prepare the capsule for reentry, should the main computer fail.[69]

According to an advertisement by HP in *Scientific American*, "Using complex programs of nearly 1000 steps written by NASA scientists and pre-recorded on magnetic program cards, the astronauts made the calculations automatically, quickly, and within ten-digit accuracy"[70] (Fig. 4.4). One often hears the tired cliché about some consumer product having more power than the Apollo Guidance Computer that took astronauts

Fig. 4.4 HP-65 programmable calculator, used by NASA. Acquired from NASA by Smithsonian National Air and Space Museum, TMS A20120307000cp07

to the Moon. In this case we have an actual pocket-sized device working *side by side* with an Apollo Guidance Computer, carrying out similar calculations.

The Legacy of the Apollo Guidance Computer and the Space Shuttle Computers

In 1971, NASA initiated a program to apply some of the technology developed in the Apollo program to aeronautics. The result was the creative use of surplus Apollo computer hardware to control a jet aircraft, in what was the beginning of modern digital "fly-by-wire" technology. Many modern aircraft, especially stealth craft like the B-2, are flown by a computer, which translates the pilot's commands to the control signals that actuate the ailerons, flaps, and rudder. Beginning with the Airbus A-320, commercial passenger jets use it as well. When NASA initiated research on the concept, the Deputy Associate Administrator for Aeronautics was none other than Neil Armstrong, who pointed out to the NASA engineers that he landed on the Moon under digital control. NASA obtained surplus Apollo hardware, and with the help of Draper Laboratories installed an Apollo Guidance Computer in an F-8 fighter. It made its first all-digital fly-by-wire flight in 1972. By all accounts the project was a success. As with the lunar module, the F-8 was controlled by only one digital computer, with an analog back-up if needed.[71]

The success did not translate into much success for Draper Laboratories, however. In 1973, while the F-8 was proving the technology, NASA was working on the design of the space shuttle's computers. Like the Apollo lunar module, the shuttle had to land under computer control. The contract for the space shuttle general-purpose computers went to IBM, not to Draper Labs. For the shuttle, IBM used a variant of its 4Pi Model AP-101 avionics computer, two of which had been used on the Skylab space station, and which IBM had produced by the thousands for a variety of military aircraft and guided missile applications.

The 4Pi shuttle computers used transistor-transistor-logic integrated circuits, in what was called medium-scale integration.[72] It did not use microprocessors, which had been invented at Intel (a Fairchild spin-off) in 1972. The computers also used magnetic core memory, produced in house by IBM and with a capacity of about half a megabyte. By the mid-1970s IBM was already shipping its mainframe computers with semiconductor memory in place of magnetic core—semiconductor memory was another advance pioneered by Fairchild.[73] As with the Block I Apollo Guidance Computer, the shuttle computers were obsolete by the time of the first shuttle flight in 1981.

The shuttle was fitted with five identical computers, four to provide fail-operational/fail-safe (FO/FS) operation. That requirement meant that a mission could continue after the failure of one computer, and the astronauts could return to Earth safely in the event of two computer failures. The fifth computer was programmed by a different software team, in the event that the other four computers had a common, possibly fatal bug in their software.[74] Each shuttle computer was configured in two units: a processor and input–output controller. Each weighed about 45 lb; thus the entire ensemble weighed about 450 lb.[75] The volume of each unit was about 1 cubic foot, for a total volume of 10 cubic feet for the five-computer ensemble. It is an implied corollary of Moore's Law that computers get smaller and lighter as the density of chips increases, as the example of the Hewlett-Packard calculator carried on the final Apollo mission demonstrated. However, the shuttle's computer complex is at least one counterexample.[76]

The shuttle's quintuple redundant system worked throughout the lifetime of the program, including the safe landing of STS-9 (*Columbia*) in 1983, after two computers failed *seriatim*.[77] The failures were traced to loose pieces of solder or other contaminants in the circuit boards. The idea of fail/operational was never put to the test; the STS-9 failure occurred as the orbiter was being positioned for reentry. The shuttle was intended to be a workhorse "space truck," making numerous flights with short turnaround times. The goal proved elusive, and perhaps the notion of fail/operational was elusive as well. John Young, Commander of STS-9, later testified that he believed that the shuttle would have been lost had he activated the fifth, back-up computer after the others had failed. His reasoning was that if the fifth computer had the same hardware problem as the other two, it too would have failed, and, by design, there was no provision for reverting to the main computer system. The fifth computer was there in the event of a common software error in the other four; it was not intended to remedy a common hardware malfunction.

Given the chance, Draper Labs would probably have used only one or two computers, with a fail/safe back-up, for the shuttle. It probably also would have chosen semiconductor memory in place of core, and microprocessors from the Intel Corporation. Would a descendent of the Apollo Guidance Computer, with its different philosophy of reliability in both hardware and software, have worked? We shall never know. In 2002, historians David Mindell and Alexander Brown of MIT interviewed Richard Battin of Draper Labs for the Apollo Guidance Computer History Project. In the interview, Battin stated that although Bill Tindall of NASA felt that Draper Labs was well qualified to get the shuttle contract, "Our laboratory would never get a contract like that again." Battin implied that the reason may have been residual resentment over the way the initial contract was awarded so early in the Apollo program without a chance for other suppliers to bid on it.[78] If there were political reasons for the choice of IBM for the shuttle computers, that is an indication of the ambiguous place of IBM in the federal government. At the same time NASA chose IBM for the shuttle, the US Justice Department was suing IBM for anti-trust violations. The suit was filed in January 1969 and dragged on through the following decade. It was dismissed in January 1982 as being "without merit." The suit was filed the year astronauts first walked on the Moon, and was dismissed less than a year after the first flight of the space shuttle.

Battin did not mention it, but there had been tension between NASA and the Instrumentation Laboratory over what NASA felt was an undisciplined research atmosphere at MIT, compared to the other contractors supplying hardware for Apollo. The lab managed to instill a more disciplined approach to software "validation and verification," after some firm prodding from NASA, and the deputizing of a programmer, John Norton, from TRW to Cambridge. Norton's job was to look over the MIT programmers' shoulders. They debugged the software by what they called the *Auge Kugel* method—German for "eyeball." In other words, you looked at the code and tried to find errors. That was the state of "software engineering" at the time. MIT programmers joked that the software was "Nortonized," and that he used a programming language called "NORTRAN." The program listings, written in a language that resembled FORTRAN, were delivered in enormous printouts. As a joke, one of the MIT programmers wrote "Norton needs glasses" in the margins of one of the printouts, expecting that either Norton would not see it, or that if he did, he would get the joke. Norton saw it and was not amused.[79] He wrote a memo on NASA letterhead that took the programmers to task. The young MIT staff came around to accepting his views. For Apollo, they delivered a remarkable set of error-free programs. After the success of Apollo, Norton returned to TRW and worked on a contract for the Bonneville Power Administration to control hydroelectric dams on the Columbia River. Among the young interns he mentored for that project was Bill Gates.[80]

Conclusion: Did the NASA Contract Jump Start the Microelectronics Revolution?

From the above discussion, it is clear that NASA alone was not responsible for the microelectronics revolution that was centered around Silicon Valley beginning in the early 1960s. Its role in innovation was nevertheless critical, in a number of ways.

The first was that the Apollo program was played out in the open. Launches were televised, the astronauts and their families were well known to the public, the technical details of the Saturn rocket and the method of lunar orbit rendezvous were explained in lay terms in great detail. The computer became a character in the drama of the landing. The world learned that Neil Armstrong had to take over manual control of the lunar module, as the computer was directing him to land in a field of boulders. That story was embellished: *all* the Apollo landings were done manually, by choice. It was not the fault of the computer that the planned landing site was not safe. The story of the "1201" and "1202" computer alarms that nearly aborted the landing was also publicized, although it would be a while before the whole story got out. The success of the Apollo missions was dramatic proof that the integrated circuit was real, and that it could be used as the foundation for complex systems.

The Minuteman contracts with Texas Instruments also demonstrated the viability of the IC, and Jack Kilby publicized that success as much as he could. Although far more Minuteman than Apollo computers were built, many aspects of the Minuteman guidance system were—and remain—classified. No Minuteman missiles were ever fired in anger. The missiles themselves were literally out of sight, buried in silos. The space race with the USSR began with the realization that the Soviet Union had developed rockets that could hurl much heavier payloads into orbit than the USA could. The USA was able to catch up with its Saturn rockets, but it also responded by focusing on more accurate guidance and better on-board electronics. This story, with its implication that the USA substituted computer power for the brute force of Soviet rocket propulsion, was also publicized.

An economic history of the IC, written in 1966 and thus before any human Apollo missions, argued that it was the military, not NASA, which played a key role: "The role of NASA in the introduction of the IC device is very negligible, if any." Yet later on the author states:

> the NASA influence had and still has a reinforcing effect for the military exhortations that preceded it. It has also raised these urgings to a level and degree of critical importance which the military could not duplicate. Military problems are more insulated and restricted to the agencies involved and their contractors. NASA's problems are more all-pervasive, simply because of the importance accorded it and the publicity which has always accompanied its mission. The general public has been involved.[81]

A second factor was the early adoption of the IC, and the buy-into the culture of innovation that was characterized by Fairchild Semiconductor. The dashed line in the graph by Rudenberg in Fig. 4.2 implies that choosing the Fairchild ICs so soon after they came on the market was unwise and risky. It worked, nevertheless. Had NASA chosen "molectronics," "cordwood," "micromodule," or any of the other competing ways of miniaturizing circuits, Americans might not have made it to the Moon by the end of the decade. That Fairchild moved on and ended up not manufacturing the Apollo chips did not seem to be a problem. MIT's choice to use a single logic device, the three-input NOR gate, rather than the multiple devices that were used in Minuteman also seems in hindsight to be correct. The Apollo computers were reliable. None ever failed during a space mission, although both MIT and Autonetics struggled with reliability problems in the early phases of their respective programs.

By choosing Fairchild and its dynamic management led by Robert Noyce, NASA was able to tap into the creative energies of what later became Silicon Valley. That led to two unanticipated consequences. These two subsequent developments hint at what later would become a shift of advanced computing from Cambridge and the manufacturers along Massachusetts' Route 128, to the west coast and Silicon Valley.

In 1964, NASA opened an Electronics Research Center (ERC) in Cambridge, where it was expected to guide the space agency's work in electronics. Intended as an equal of the other NASA centers, it was located in Kendall Square, on the MIT campus and a few streets away from the Instrumentation Laboratory. It closed in 1970, however.[82] Political issues played a role: members of Congress wondered why it could not be their congressional district, and the decision to locate the ERC in Cambridge got tangled up in the 1964 campaign by Edward M. Kennedy for Senator.[83] There were technical reasons as well: other NASA centers had been doing electronics research and had established close relations with industrial firms, and they were not sure how they were to cooperate with the new center, if at all. The ERC never found its footing, and struggled while the semiconductor and computer industries were making giant strides on their own.[84]

The MIT Instrumentation Laboratory also did not fare well. In 1969 it was the target of anti-war demonstrations, which could not have helped NASA's perception of the lab.[85] In the late 1960s, the academic culture of Cambridge did not mesh well with the culture of IBM or NASA, whose center of gravity was in the south. The lab was renamed in honor of Charles Stark Draper the following year and later was administratively separated from MIT. As for NASA's decision to go with IBM for the shuttle computers, perhaps politics was involved, as Richard Battin hinted. Another factor was that the Instrumentation Laboratory had little experience in marketing. Those who chronicle the rise of Silicon Valley always emphasize the marketing savvy of people like Noyce and his brethren. Jack Kilby played a similar role for Texas Instruments. That was never part of the lab's culture.

Looking back on Apollo, one cannot help but admire the genius of its computer designers, who had to design a system to guide astronauts to the Moon and back at a time when computers were programmed by punched cards and took up entire rooms that had false floors to hide the cabling and air conditioning. The flawless performance of the Apollo software, written for a machine with a tiny amount of core memory, was as much of an accomplishment. The decision to use integrated circuits was a bold one, and risky, but it paid off. One may contrast that decision with the more conservative approach that NASA took toward the shuttle avionics system, although it would not be fair to judge the shuttle program too harshly. To sum up, NASA's role in the creation of the microelectronics "revolution"—a term that belongs in quotes—was not the deciding factor, but it was significant.

Notes

1. In 1969, the MIT Instrumentation Laboratory changed its name to the Charles Stark Draper Laboratory, by which it is known to this day. This narrative uses the name that was current at the time.
2. Thomas J. Misa, "Military Needs, Commercial Realities, and the Development of the Transistor, 1948–1958," in Merritt Roe Smith, ed., *Military Enterprise and Technological Change* (Cambridge, MA: MIT

Press, 1985), 253–87; also Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech*, 1930–1970 (Cambridge, MA: MIT Press, 2006).
3. David A. Mindell, *Digital Apollo: Human and Machine in Spaceflight* (Cambridge, MA: MIT Press, 2008); Eldon C. Hall, *Journey to the Moon: The History of the Apollo Guidance Computer* (Reston, VA: AIAA, 1996); James E. Tomayko, *Computers in Spaceflight: The NASA Experience*, in Allen E. Kent and James G. Williams, eds., *Encyclopedia of Computer Science and Technology*, vol. 18, Supplement 3 (New York: Marcel Dekker, 1987).
4. Michael J. Mahoney, "The History of Computing in the History of Technology," *Annals of the History of Computing*, 10/2 (1988), 113–26. The phrase appears on 115.
5. The role of the suite of large mainframe computers at NASA's Johnson Spaceflight Center in Houston, which did a lot of the processing necessary for a successful mission, is not discussed here.
6. Frederick I. Ordway III and Mitchell R. Sharpe, *The Rocket Team: From the V-2 to the Saturn Moon Rocket* (Cambridge, MA: MIT Press 1982), Chap. 19.
7. Edgar Durbin, "Saturn I Guidance and Control Systems," in *Quest: The History of Spaceflight Quarterly*, 17/4 (2010), 19–31.
8. Ibid. 28.
9. Mindell, *Digital Apollo*, 139–140.
10. "The Next Revolution in Electronics," *Business Week* April 14, 1962, 160–164.
11. Emerson W. Pugh, Lyle R. Johnson, and John H. Palmer, *IBM's 360 and Early 370 Systems* (Cambridge, MA: MIT Press, 1991), 105.
12. Ibid., 108.
13. Martin Campbell-Kelly and Daniel D. Garcia-Swartz, *From Mainframes to Smartphones: A History of the International Computer Industry* (Cambridge, MA: Harvard University Press, 2015), 75–76.
14. Memorandum, David W. Gilbert, Manager, Spacecraft System, Guidance and Control, NASA MSC, for distribution, September 30, 1963. Copy in author's files.
15. Representative Joseph E. Karth (D-Minnesota) to NASA Administrator James E. Webb, February 15, 1965. Copy in author's files; also High Blair-Smith, "How the Big Blue Grinch Stole the Apollo Guidance Computer… Only they Didn't!" Paper presented at the 2005 Military and Aerospace Programmable Logic Device (MAPLD) International Conference, September 7–9, Washington, DC. NASA, Office of Logic Design.
16. Karth, Ibid.

17. David G. Hoag, "The History of Apollo On-Board Guidance, Navigation, and Control," in Ernst A. Steinhoff, ed., *The Eagle Has Returned*, Volume 43, Science and Technology, supplement to Advances in the Astronautical Sciences (San Diego: American Astronautical Society), 284.
18. Jayne P. Hanley, private communication, July 16, 2015. Hanley was a physicist who worked on failure mode analysis for the Apollo project. She also wrote limericks that chronicled the work at the Instrumentation Laboratory.
19. James Phinney Baxter 3rd, *Scientists Against Time* (New York: Little, Brown, 1946), 226–27, and photograph opposite 227.
20. Gordon E. Moore, *Electronics*, April 19, 1965, 114–117.
21. H. G. Rudenberg, "Large-Scale Integration: Promises versus Accomplishments—the Dilemma of Our Industry," in *Proceedings, 1969 Fall Joint Computer Conference*, November 18–20, 1969, Las Vegas, Nevada. Vol 35 (1969), 359–67.
22. Earnest Braun and Stuart Macdonald, *Revolution in Miniature: the History and Impact of Semiconductor Electronics re-explored in an Updated and Revised Second Edition* (Cambridge, UK: Cambridge University Press1982; Michael Riordan and Lillian Hoddeson, *Crystal Fire: the Birth of the Information Age* (New York: Norton, 1997).
23. Carolyn Caddes, *Portraits of Success: Impressions of Silicon Valley Pioneers* (Palo Alto, Tioga Publishing Company, 1986), 44–45.
24. Riordan & Hoddeson, *Crystal Fire*, Chap. 11.
25. Michael F. Wolff, "The Genesis of the I.C." *IEEE Spectrum* (August 1976): 45–53; also Fairchild Semiconductor, "Facts About Fairchild," pamphlet ca. 1966. Computer History Museum, Mountain View, Archives, folder 102710165; also M. Smollett, "The Technology of Semiconductor Manufacture," *The Radio and Electronics Engineer*, 43/1–2 (January–February 1973): 29–38.
26. Eldon Hall, *Journey to the Moon*, Chaps. 6, 7.
27. "More Apollo Guidance Flexibility Sought," *Aviation Week and Space Technology*, November 16, 1964, pp. 71–74; Joe Shea, quoted in Rex Pay, "First of Some 50 Block II Apollo G&N Computers is Due by Mid-1965," *Missiles and Rockets*, September 7, 1964, 37.
28. Rex Pay, "First of Some 50 Block II Apollo G&N Computers," 36–37.
29. Walter Johnson, "Schriever hits 'Nickle & Dime' Part Failures," *Electronic News*, February 26, 1962, pp. 1, 18; also Philip Klass, *Aviation Week,* April 8, 1957, 93.
30. Rockwell International, Autonetics Group. "The Success Story of Minuteman," pamphlet, revision dated October 1977. National Air and Space Museum Tech files.

31. Philip Klass, “Systems Keyed to Fast-Reaction Demands,” *Aviation Week & Space Technology*, October 29, 1962, 57; also Rockwell International, “The Minuteman High Reliability Component Parts Program: A History and Legacy (Anaheim, CA: Rockwell International, Autonetics Strategic Systems Division, July 31, 1981, 1.
32. Rockwell, “Minuteman High Reliability,” Chap. 1.
33. Ibid., 7, 14. In his memoir, Grumman engineer Tom Kelly recalls a visit he made to a manufacturer of batteries for the Apollo lunar module. He describes observing a worker assembling a battery who was smoking a cigarette, with the ash growing longer and longer, until it finally “broke off and fell into the assembly.” Kelly, *Moon Lander: How we Developed the Apollo Lunar Module* (Washington, DC: Smithsonian Institution Press, 2001), 138–39.
34. Fairchild Semiconductor, “Facts about Fairchild,” brochure ca. 1966, Computer History Museum Archives, folder 102710165; also Eldon Hall, *Journey to the Moon* (1996), Chap. 12.
35. High-performance jet aircraft used Kovar as the frame for the cockpit windows, to prevent the windows from cracking as the aircraft went through temperature extremes.
36. “Facts About Fairchild,” p. 12; also “Leadwire,” (employee newsletter), May 1966, 3–4. Computer History Museum Archives, folder 102710151.
37. “Nobel Prize in Physics, 2000,” http://www.nobelprize.org/nobel_prizes/physics/laureates/2000/kilby-bio.html. Accessed July 29, 2015.
38. “Fairchild Scores a Point on Circuits,” *Business Week*, November 29, 1969, p. 128; also T. R. Reid, *The Chip*: (New York: Simon & Schuster, 1985), Chap. 5.
39. “Fairchild Scores a Point,” ibid.
40. Fairchild Semiconductor, “Comparative Report on TI Series 51 Solid Circuits,” June 13, 1963. Computer History Museum Archives, Folder 102708031.
41. See, for example, Laurence D. Shergalis, “Microelectronics—a New Concept in Packaging,” *Electronic Design*, April 29, 1959, 32–48, for an example of the myriad and incompatible techniques for miniaturization then under development.
42. Different reports, including several notes by Kilby himself, give varying numbers, from 18 to 24. Letter, J.S. Kilby to Gwen Bell, June 26, 1984, Computer Museum (Boston) Archives. Copy in author’s possession. The Smithsonian Institution’s National Museum of American History has an extensive collection of early TI chips, information on which is available at http://smithsonianchips.si.edu/texas/t_421-14.htm. The Smithsonian site says there were 19 types of circuits.
43. Lécuyer, *Making Silicon Valley* (2006), 238–245.

44. Kilby to Bell, ibid.
45. "Minuteman is Top Semiconductor User," *Aviation Week*, July 26, 1965, 83.
46. Barry Miller, "Microcircuits Production Growth Outpaces Applications," *Aviation Week and Space Technology*, November 16, 1964, 76–83; also "The Next Revolution in Electronics," *Business Week*, April 14, 1962. Noyce's biographer says that the decision to cut prices was made by Noyce in the spring of 1964: Leslie Berlin, *The Man Behind the Microchip: Robert Noyce and the Invention of Silicon Valley* (Oxford University Press, 2005), 137.
47. Tom Wolfe, "The Tinkerings of Robert Noyce: How the Sun Rose on Silicon Valley," *Esquire*, December 1983, 346–74.
48. Don. C. Hoefler, "Silicon Valley, USA," *Electronic News*, January 11, 1971, p. 1, 4–5; January 18, 1971, 1, 4–5; January 25, 1971, 4–5.
49. Eldon Hall, *Journey to the Moon*, 51.
50. A. Michal McMahon, "The Computer and the Complex: A Study of Technical Innovation in Postwar America," Washington, DC: NASA History Office, October 1986; also David G. Hoag, "The History of Apollo On-Board Guidance, Navigation, and Control," in Ernst A. Steinhoff, ed., *The Eagle Has Returned*, Volume 43, Science and Technology, supplement to Advances in the Astronautical Sciences (San Diego: American Astronautical Society), 270–300.
51. Eldon C. Hall, "MIT's Role in Project Apollo," Final Report on Contracts NAS-9-153 and NAS 9-4065; Volume III: Computer Subsystem, August 1972. Cambridge, MA: Charles Stark Draper Laboratory.
52. NASA Goddard Space Flight Center, Greenbelt, MD, "Data Book for Environmental Testing and Evaluation, Unit 1: Delta, S-16 (Orbiting Solar Observatory—OSO-1). Most historical accounts state that the first operational use of ICs in space was on the Interplanetary Monitoring Platform (IMP-A), launched in November 1963. In both spacecraft the chips were supplied by TI, and they functioned well.
53. Floyd E. Kvamme, *Fairchild Semiconductor Integrated Circuits*, (Mountain View, CA: Fairchild Semiconductor, 1966), 3–4.
54. Eldon Hall, *Journey to the Moon*, 19, 184–87.
55. Hall, "MIT's Role in Project Apollo," 61–62.
56. Hall, *Journey to the Moon*, Chap. 12.
57. During the Apollo 11 landing, the computer was overloaded due to the rendezvous radar being switched on, which was not documented in the preparations for the mission. The computer handled the overload without jeopardizing control of the landing. During the Apollo 14 mission,

a faulty switch could have led to an aborted landing, but a quick workaround by Draper Lab's programmers allowed the crew to reprogram the computer and land safely.

58. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch, eds. *The Social Construction of Technological Systems* (Cambridge, MA: MIT Press, 1987).
59. Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech*, 1930–1970 (Cambridge, MA: MIT Press, 2006).
60. Eldon Hall, *Journey to the Moon*, Chap. 10.
61. "Performance of Apollo G&N, 9 November 1967,"Memorandum, David G. Hoag to MIT Instrumentation Lab Employees, December 4, 1967; also "G&N Performance in Apollo 5 and Apollo 6 Flights," Apollo Project Memo No. 1893, April 22, 1968.
62. Pat M. Kurten, "Apollo Experience Report, Guidance and Control Systems: Lunar Module Abort Guidance System," NASA Johnson Space Center, NASA Technical Note NASA TN D-7990, July 1975.
63. TRW Systems Group, Redondo Beach, California, "Lunar Module/Abort Guidance System (LM/AGS) Design Survey," N69-33430. NASA Electronics Research Laboratory Contract NAS 12–110, September 1968.
64. Signetics Corporation files, Computer History Museum Archives, Mountain View, CA, Box 32, folder 102711711.
65. Kurten, "Apollo Experience Report," (1975), 64.
66. U.S. National Research Council, "The Future of Computing Performance: Game Over or Next Level?" Washington, DC, National Academies Press, 2011.
67. Paul E. Ceruzzi, *A History of Modern Computing*, Second Edition (Cambridge, MA: MIT Press, 2003), 65–66, 130.
68. Leslie Berlin, *The Man Behind the Microchip*, 135.
69. "HP-65 in Space With Apollo-Soyuz," advertisement in *Scientific American*, September 1975, 19; also W. C. Mier-Jedrzejowicz, "A Guide to HP Handheld Calculators and Computers," (Tustin, CA: Wilson/Barnett Publishing, 1995), 21–22.
70. Hugh Blair-Smith, "How the Big Blue Grinch…" (2005); also Jack E. Volder, "The CORDIC Trigonometric Computing Technique," *IRE Transactions on Electronic Computers*, EC-8 (September 1959), 330–334.
71. James E. Tomayko, *Computers Take Flight: A History of NASA's Pioneering Digital Fly-by-Wire Project* (Washington, DC: NASA History Office, 2000, NASA SP-2000-4224.
72. P.F. Olsen and R. J. Orrange, "Real-time Systems for Federal Applications: A review of Significant Technological Developments," *IBM Journal of Research and Development*, 25/5 (September 1981): 405–16.

73. Ceruzzi, *A History of Modern Computing*, 196–197.
74. A. E. Cooper, "Shuttle Computer Complex: a Redundant, Cooperative Computer Set," in IBM Corporation, "Space Transportation and Ground Control Systems: The IBM Role," compiled reprints from *Technical Directions*, a quarterly publication from the IBM Federal Systems Division, 1–10.
75. National Air and Space Museum, General Purpose Computer catalog # A19950160000; I/O controller A19950161000.
76. This comparison leaves out the Saturn V Launch Vehicle Digital Computer, which weighed approximately 160 kg (74 lb).
77. NASA, Space Shuttle Mission Archives, STS-9: http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-9.html. Accessed August 11, 2015.
78. http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/interviews/battin.htm. IBM also divested its Federal Systems Division and no longer is involved with manned spacecraft computing in a major way. The former Owego, New York plant where the shuttle computers were built is now (2015) owned by Lockheed Martin.
79. Margaret Hamilton, Interview with the author, March 15, 1986, Cambridge, MA.
80. Susan Lammers, *Microsoft at Work* (Seattle, WA: Microsoft Press, 1986), 84; also Stephen Manes and Paul Andrews, *Gates: How Microsoft's Mogul Reinvented an Industry and Made Himself the Richest Man in America* (New York: Doubleday, 1993), 54. Whether or not it is even possible to "reverse-compile" is an open question, but several people have told the author that Norton had that ability.
81. Kleiman, "The Integrated Circuit…" (1966), 207–210.
82. NASA History Office, "Electronics Research Center," http://history.nasa.gov/erc.html. Accessed August 11, 2015.
83. Kennedy, the youngest brother of the slain President, had won a special election in 1962 for the Senate, and in 1964 he ran in the 1964 regular election, and won.
84. NASA Electronics Research Center Chronological Files, Folder 8566, NASA History Office, Washington, DC.
85. Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press1993), Chap. 9.

CHAPTER 5

NASA's Mission Control Center: The Space Program's Capitol as Innovative Capital

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NASA's Mission Control Center in Houston, TX, epitomized how cutting-edge computing and communications technologies enabled control within previously inaccessible environments in the middle of the twentieth century. The Mission Control Center, or MCC, began directing spaceflight operations in 1964, and its architectural design soon became a template for any organization that wished to project an image of confidence and technological savvy. Operators at workstations retrieved data from the most advanced technological tracking systems of the day in real time, and massive screens filled with aggregate data faced these stations to help facilitate complex missions. This aesthetic has its roots in NASA and military command-and-control room predecessors, such as the headquarters of the Strategic Air Command; however, the construction of the MCC also required novel design approaches particular to the needs of the space organization, which were innovated by NASA staff and contractors. The MCC in Houston became the most recognizable of these spaces, solidifying this command center

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configuration archetype in the public consciousness and securing responsibility for its continued ubiquity both in practice and in popular culture.

The MCC also served as a symbol of political and military authority during the Cold War. When considering the economic impact and legacy of the American spaceflight program, it becomes clear that its value cannot simply be expressed in fiscal terms. Instead, it also needs to be measured in terms of the prestige, faith, trust, and hope for the future that its organizational structure and technological savvy instilled in the American public. The modernist, efficient styling of the MCC allayed domestic fears while showcasing engineering prowess. Its architecture both symbolized and physically embodied the country's potential to triumph over the USSR through its support for spaceflight feats of technological sophistication. These demonstrations also carried more implicit threats—as is true today, to innovate in aerospace technologies strongly correlates with a nation's economic, political, and military dominance. While no one at NASA ordered that the MCC be designed specifically with these goals in mind, its public relations team was happy to provide photos of the center to the media which highlighted NASA's confidence and technological wizardry. This attention led to the commodification of the center itself in terms beyond its operational functions, and the resultant additional value contributed to the success of the nascent organization by way of generating taxpayer support and revenue.

It is difficult to quantify the intangible economic value created by this physical representation of American technological strength. A manageable and equally profitable ambition, however, is an examination of how and why the MCC was envisioned, constructed, and lives on in US culture. This history not only highlights the significance of the space program in Cold War America, but also informs future programs which might construct physical facilities that serve scientific and political, as well as economic, ambitions.

A Complex Story

The available literature on NASA's Mission Control Center in Houston focuses almost exclusively on how people within the room supported spaceflight feats.[1] Certainly, the achievement of landing a human on the Moon, the dramatic rescue of three astronauts during the life-threatening circumstances of Apollo 13, and other space triumphs deserve recollection. Ground controllers proved that support from Earth could save lives in space, and their accomplishments throughout the history of the American space program must be recounted.

This approach, however, neglects one of the MCC's most crucial aspects: the innovation of Mission Control itself. In the early 1960s, new communications technologies and high-speed computer processors made the creation of this high-tech ground control station possible. Its design assembled technologies which enabled people to tackle real-time ground control of space missions, and this was a notable achievement. After the initial forays into space undertaken during the Mercury missions, NASA administrators recognized the need for a more technologically sophisticated mission control center to support the Gemini and Apollo programs. They knew that state-of-the-art computers, displays, and communications equipment would be crucial components of the new center, but they did not have any (unclassified) existing model on which to base its design. NASA delegated this task to contractors, namely Philco Western Development Laboratories, a division of Ford.[2]

Employees at Philco tasked with the creation of Mission Control Houston conceived the space, prioritized the layout, and created power relations via design that would accommodate users in the completion of tasks.[3] Philco's assemblage resulted in the most famous iteration of a particularly mid-century technology: the global control center. The MCC in Houston, filled with consoles and computers and displays of real-time data, became iconic. This is evidenced by its ubiquity in both military and civilian operations, from American defense headquarters to casino surveillance rooms. Insufficient historical treatment of NASA's MCC has resulted in the neglect of roles that contractors have played (and currently play) in the US space program. NASA has long been one of the largest customers of the American aerospace industry. Explicit acknowledgment and examination of the space agency's contractors showcase another instance of the federal government creating demand for, and to a certain extent subsidizing, aerospace companies.[4] The story of the construction of the MCC allows for a number of previously ignored connections to be recounted.

Christopher "Chris" Columbus Kraft, Jr., best known as Flight Director during the first decade of the agency's activity, is often credited with the design of NASA's control centers.[5] The first American space that was dedicated to tracking space capsule movements was called the Mercury Control Center (MCC), and it was built in a former photography warehouse at what is today the Kennedy Space Center in Cape

Canaveral, FL in 1959.[6] Kraft recalled in his memoirs that he did not know who started calling the room *mission* control, as "MCC had meant Mercury Control Center to us, but *mission* control was okay, too. It had a nice ring to it."[7]

Kraft had strong ideas about the proper layout and functionality of this room. He did not want the command center to be a site of mere passive surveillance; instead, the space needed to allow people to actively take part in the missions and to remotely support flights.[8] To start, Kraft and his operations team considered the types of consoles they would need, including an environmental systems console, which would be monitored by a flight surgeon; a systems console, to be watched by an engineer; a communications console, whose operator would relay all messages between the MCC and a capsule (which would most likely be manned by an astronaut); a console to keep track of the worldwide network of remote sites, to be monitored by someone from the Department of Defense (DoD); a console to monitor the rocket; a flight director's console; and a procedures console, which was the "hall monitor" and kept track of every procedure for every console in the configuration. Kraft noted that this last position would later be filled with his "alter-ego" or right-hand man (even though he would be physically located on Kraft's left side).[9]

Sensitive to the needs of bureaucracy, Kraft noted that additional consoles would be needed, even if they were not directly related to flight operations. Each operations director would need a place, as would senior officials from the DoD, a public affairs officer, and contractors. All of these positions would work together to remotely monitor—and eventually control—spaceflight from a central location. A separate, adjacent command center was tasked with the responsibility of recovering capsules.[10] After dedicating so much careful thought to the design of Mercury Control, Kraft was understandably angered when rocket guru and German émigré Werner Von Braun said that ground control of a space flight was a "dumb idea." Kraft recalled that if Von Braun had said that phrase one more time, he might have punched him.[11] This disagreement underscores the originality of Kraft's ambition for the ground control of spaceflight.

To supplement the consoles, contracted employees from Philco and Western Electric designed and built the huge, now iconic, front wall display for Mission Control in Florida. It was a large map of the world, which tracked a capsule's progress as it was detected by different radar stations around the globe. Kraft was initially skeptical of its utility. He recalled, "It was a beautiful display. I understood what it was for, but I still thought it was superfluous." He quickly changed his mind, however, admitting that "[t]he map was filled with vital information. The graphic format made it easy to grasp. A Mercury capsule symbol moved along the sine wave, or ground track. I knew instantly where it was."[12] Flight Controller, and later Flight Director, Gene Kranz remembered the map in somewhat less glamorous terms, recalling watching a "toylike spacecraft model, suspended by wires, mov[ing] across the map to trace the orbit."[13]

For the Mercury program, NASA was dealing with simple, one-man spacecraft. There were no extravehicular activities (or "spacewalks"), no maneuvering, no guidance, no rendezvous. The missions of Gemini and Apollo would require the ability to complete all of these tasks.[14] And even Project Mercury's relatively simple orbital missions, such as the one that carried John Glenn, necessitated constant updating of equipment and procedures. The communications system was particularly limited, as there was not a global network at the time; remote monitoring sites took up to fifteen minutes to respond to Mercury Control Center queries.[15] The upcoming Gemini missions would necessitate yet more technologically complex monitoring. It became clear that the system would have to be completely retooled, and NASA engineers recognized that off-the-shelf electronics gear would be insufficient to control future missions.[16] They would need to custom design an entirely new control center, and a cornerstone of this upgrade would involve the computer system.

The deficiencies of the Mercury Control Center computer set-up further underscore the problem. The machines that ran the system at Cape Canaveral were actually located hundreds of miles away, in an IBM building on Washington, DC's Pennsylvania Avenue. Tracking data was sent north from Florida, the computers in DC processed trajectories, then sent this information over telephone lines back to the Cape, and finally the information was available for display on the control center's plot board. Glynn Lunney, the Flight Dynamic Officer at Mercury Control Center, allowed that he found it "a relatively crude system." As far as getting data to consoles, there were not any television screens to display telemetry data, but only mechanical meters.[17]

For the new center, this outdated meter system would be transitioned to a digital computing schema. This proposed upgrade worried some operators. NASA controller Rodney "Rod" Loe recalled that NASA personnel who had worked on Mercury felt more secure with viewing data on meters, because they were "hard meters, and the meters had limits, you could set [them]. You [could] pull a tab down, and then if the needle got above that tab, you'd get a red light." This physical interaction with the consoles was important to its operators. As Loe explained, with digital computers, "Here was another piece of equipment that could fail, that would be between us and the spacecraft, and would cause us to lose data." It was a concern that paralleled the concerns of pilots transitioning to instrument flying—users needed to learn to trust the computers. To ease the transition, when computers replaced the meters in the later control center, data was displayed on digital representations of meters. Operators later admitted that it was silly to have the computer depict data on graphical meters, but it is illustrative that the transition to a digital format was not an obvious choice.[18]

The change from meters to digital displays is anecdotal of the scope of changes needed within the Mission Control Room to support the next decade of planned NASA missions. The number of upgrades required was large—too large to implement within the existing space in Cape Canaveral. Kraft noted, "To manage and control missions to the moon, we'd need a new and bigger center, along with changes still unknown in the worldwide tracking network."[19] In 1961, Kraft, along with fellow NASA employees Dennis Fielder, Tec Roberts, and John Hodge, initiated a study to determine the location for a new command center.[20] After rejecting a move to the Goddard Space Flight Center, due to that facility's small size and managerial conflicts, Kraft and his team looked to other potential sites. NASA administrators required that the location include

> access to water transportation by large barges, a moderate climate, availability of all-weather commercial jet service, a well established industrial complex with supporting technical facilities and labor, close proximity to a culturally attractive community in the vicinity of an institution of higher education, a strong electric utility and water supply, at least 1000 acres of land, and certain specified cost parameters.[21]

Houston fit the bill on almost all of these counts, and it surely did not hurt that it was located within Vice President Lyndon Johnson's home state of Texas, as well as in the congressional district of Albert Thomas, the chairman of the body that oversaw NASA's budget.[22] The city of

Houston enthusiastically welcomed the space agency and was particularly pleased that local firms received 29 of NASA's 32 subcontracts for the design and construction of the site.[23] On September 19, 1961, NASA announced that a new "spaceflight laboratory" would be located in Houston on 1000 acres of land that was donated to the government by Rice University (another 600 acres were purchased to give the site direct access from the highway).[24] Gene Kranz later admitted that he initially thought that the control center should have remained near the launch site in Cape Canaveral, but it was convenient to be located near a feeder university like the University of Houston, from which NASA could recruit young people with technical training in things like cryogenics and computers, and who lent a "youthful exuberance" to the workplace.[25]

The Manned Spacecraft Center (MSC), as NASA officially named the complex until it was renamed the Lyndon B. Johnson Space Center in 1973, was built about 28 miles south of downtown Houston, close to the shore of Clear Lake, which provided access to Galveston Bay.[26] Within the 1600-acre site, NASA built MSC Building 30, which housed the Mission Control Center, in November 1964.[27] This three-story structure consisted of a Mission Operations Wing, an Operations Support Wing, and an interconnecting Lobby Wing. The Mission Operations Wing was built by the Army Corps of Engineers and a general contractor, ETS-Holden-Galvin. The Corps of Engineers selected the architect and construction firms. Their choice—the Texas firm Brown & Root and the designer Charles Luckman of Los Angeles—received a $1.5 million design contract for the center.[28] Once the building's exterior structure was in place, the interior space was ready to be outfitted with computers, communications links, and consoles.

Building the Mission Control Center

To meet Gemini mission requirements, the new Mission Control Center (Fig. 5.1) needed increased mission performance awareness via real-time data displays. Flight controllers would be stationed at consoles, as they had been at the center in Florida, at which they would receive critical mission information via computer screens. This space was officially named the Mission Operations Control Room (MOCR), and there were actually two of them: identical and located on the second and third floors of Building 30.[29] These Flight Control Rooms (or FCRs, pronounced 'Fickers') were where flight controllers got information from personal console computer

Fig. 5.1 This overall view of NASA Mission Control Center (MCC), Houston, TX, was taken during the Gemini V flight of August 21–29, 1965. Note the screen at the front of the MCC which is used to track the progress of the Gemini spacecraft. (NASA, image number S65-45280, public domain). Available at https://spaceflight.nasa.gov/gallery/images/gemini/gemini5/html/s65-45280.html

displays, or from projected displays on the wall at the front of the room, where they would work "feverishly at their consoles, headsets in place." The third-floor FCR was primarily designated to monitor DoD payloads, but either space could be used as NASA's manned spaceflight mission control, or two missions could be conducted simultaneously.[30] These innovative spaces, each approximately 100,000 square feet, housed the minds which directed America's space program, as well as becoming ubiquitous and iconic in US popular culture. This room became commonly known among the public as "Mission Control."[31] While the technological sophistication of the room and the accomplishments of its inhabitants have been well documented in popular media, its origin story has remained largely unquestioned. Its construction was, in fact, an innovative investment on the part of NASA, one that should be largely credited to the contractors who created a control room for the future.

Prior to the construction of Building 30, NASA hired two contractors to design the computer system and operational layout of Mission Control. In 1962, IBM was awarded the Real Time Computer Complex (RTCC) contract to build a complex digital command system which could control the Gemini spacecraft, its target vehicle Agena, and the Apollo craft. The final design consisted of five IBM 7094 main processors using a customized IBM operating system. This system processed "telemetry, trajectory and command data. The data was routed to recorders, meters, and the digital-to-TV displays."[32] Also in 1962, Philco-Ford was contracted to perform a development study for "Manned Space Flight Operation Control and Support" in Houston. Primarily a human engineering study, it explored how data processing and display systems, which would be powered by the underlying IBM architecture, would work together in a holistic way that best promised mission success.[33]

For anyone acquainted with the history of electronics, Philco may seem an odd candidate for designer of NASA's MCC, but the company—once a pioneer in early radio and television products—had changed hands and focus by the 1960s. Philco had begun cultivating aerospace contacts and had acquired work within the industry. Ford acquired the enterprise in December 1961, to produce car radios and other electronics.[34] A former employee speculated that Ford's acquisition of Philco was a marketing ploy meant to cultivate a high-tech image to sell to the well-endowed space program.[35] Regardless of the company's motivations, the strategy worked. In 1963, Philco-Ford Western Development Laboratories (WDL) was awarded the NASA contract for the design, development, implementation, maintenance, and operation of the Mission Control Center in Houston (MCC-H). This contract required that Philco-Ford WDL establish Philco-Ford Houston Operations (PHO), which would be awarded further contracts for maintaining and upgrading the center in the following years.[36] In 1965, for example, Philco replaced almost 400 black-and-white scanners with color televisions in Mission Control.[37]

So much support was needed, in fact, that a headquarters for PHO was built near the Manned Spacecraft Center, which accommodated approximately 500 employees.[38] Philco advertisements from the time detailed visions of a future in which many tasks would be automated by computers and processes would be visualized on gigantic television screens.[39] NASA directors, such as Chris Kraft, held the same sort of vision for Mission Control, although they did insist that responsibilities be delegated to particular flight consoles in the same way that they had been at the Mercury Control Center. It was Philco's job to implement this vision in Houston.

The project was spearheaded by Philco's program director for the design of the MCC, Walter "Walt" LaBerge. Born near the north side of Chicago in 1924, he was inclined toward a liberal arts education, especially after covering sports for his high school newspaper, but his father convinced him that pursuing an applied science education at Notre Dame would be more prudent from a job security standpoint.[40] LaBerge went to the university in 1941 as a physics major, and also enrolled in Notre Dame's Reserve Officers Training Corps (NROTC) program. In July 1943, due to the escalation of World War II, he and his classmates became full-time Navy seamen, versus civilians enrolled in the NROTC program with draft deferments. Upon graduation with a Bachelor of Naval Science degree in January 1944, LaBerge was commissioned and sent on active duty. After the war, he returned to Notre Dame to finish his Bachelor of Science degree in physics, and due to the opportunity afforded by the GI Bill, he decided to pursue a Ph.D. in the field. After completing his graduate work, and due to his Naval Reserve status, he relocated to the Naval Ordnance Test Station, China Lake, CA, which was located in the middle of the Mojave Desert. LaBerge noted in retrospect that jobs were lean, as physicists were not yet in high demand, as they would be after Sputnik ushered in the space race.[41] While at China Lake, he co-invented the Sidewinder heat-seeking air-to-air missile, for which he received much acclaim, and which explains how he ended up working for Philco-Ford.

Philco Research Laboratory in Philadelphia was contracted to produce the engineered version of the Sidewinder guidance unit. In 1957, the head of the Philco team asked LaBerge if he would be interested in joining him in a new Philco venture in Palo Alto, CA; the company had recently received a contract from Lockheed in Sunnyvale that necessitated a local presence. LaBerge decided to leave government service and try his hand at a management position in the private sector. It was an exciting time to join the aerospace industry. In 1961, President Kennedy committed the nation to sending a man to the Moon before the end of the decade, and the industry scrambled to design rockets, spacecraft, and ground launch and control systems. To secure the contract for the design of MCC for Philco-Ford, LaBerge cited the company's impressive high-tech track record in a presentation given to NASA executives. He noted that Philco's WDL had developed *Courier*, the first active repeater satellite; had performed classified work for the Air Force; and had constructed military antennas and telescopes as part of a military communications satellite system.[42] He recalled the atmosphere in which he gave the presentation as quite intimidating. "[Chris Kraft] and his staff were clustered around an auditorium built like a gladiator's fighting pit," he wrote in his memoirs. "It was so much so that I almost blurted out as I began my presentation the traditional 'We who are about to die salute you.'"[43] Joking aside, LaBerge thought in retrospect that the selection officials at NASA chose Philco because they were convinced that the contractor could meet deadlines and would be easy to work with. The resulting contract was worth $33.8 million out of the total MCC cost of $100 million.[44]

LaBerge was named the general operations manager of Philco's Houston operation, for which he headed a task force which included scientists, engineers, technicians, and administrative personnel. He had a difficult time recruiting for this venture, probably because, as he admitted, "[Houston] was thought to be about the world's worst place to live."[45] (NASA had the same problem: the hurricane-prone area did not entice potential transplants.) It soon became apparent that LaBerge's team was not large enough to complete the "low-tech, manually intensive" work of wiring connectors to computers to consoles and then making and verifying "literally a zillion connections."[46]

Further, the Philco team initially did not have good relationships with IBM, the RTCC contractor. LaBerge mused that the computer company had a superiority complex and did not appreciate being a subcontractor to Philco.[47] It likely resented that it was only due to Philco's benevolence that the RTCC used a 5-IBM 7094 configuration for Mission Control, instead of Philco opting for its own systems, which resulted in a $36 million contract for Big Blue.[48] James "Jim" Satterfield, an aerospace technologist for NASA, concurred that "[IBM] sure didn't want anybody like Philco telling them what to do."[49] It was necessary to cultivate a professional working relationship, however, as the computers and the display systems needed to be integrated. The project moved along after a slow start, and the Philco team soon was responsible for having constructed one of the most iconic control rooms in American history.

While LaBerge's administrative acumen led to the successful completion of the Mission Control Room, other men played large roles in the technical design and implementation of technologies within the space. One was Otto G. Schwede, a German scientist brought to the USA after World War II as part of Project Paperclip. Born in 1912, Schwede was one of 12 German scientists, primarily aircraft, rocket, and missile specialists, brought to work at the Naval Air Missile Test Center in Point Mugu, CA in 1947. Schwede became technical director for the Range Instrumentation department there, and filed a number of patents during the 1950s, including the Angular Discriminating Ocular Device, an engine fuel flow regulator, and an isotope separator.[50] By 1960, all of these émigrés had left Point Mugu, either to start their own companies or to work in private industry.[51]

Along with fellow Paperclip member Theodore Sturm, who had headed the Guidance Division at Point Mugu and had worked on the V-2 program in Germany, Schwede founded an industrial research laboratory, the Electronic Systems Development Corporation in Ventura, CA. The company focused on special-purpose digital and analog computers, solid-state electronic devices, liquid rocket engine control malfunction protection systems, and other instrumentation and control systems. One former employee recalled that Schwede and Sturm were "brilliant guys."[52] With these credentials and level of expertise, is no wonder that Schwede was recruited by Philco to be Chief Engineer in Houston, responsible for designing the technical aspects of the MCC. LaBerge referred to Schwede as a "crusty old German Paper Clip," while also asserting that he "truly enjoyed and trusted Otto, but most everyone else feared to work with him because of his unbridled competence and crustiness."[53] Personal demeanor aside, Schwede's work for Philco is preserved in the comprehensive technical reports that he prepared for NASA, which showcase the detailed thought processes and expertise behind the Philco team's design choices.

The first report in a series of eight prepared for NASA by Philco in 1962 focused on what facilities would be required within MCC. The company considered the needs of the room in great detail, giving thought to demands involving power, structural integrity, air conditioning, noise levels, and personnel's access to equipment.[54] With this foundation, the next document considered how equipment would be integrated to support Gemini and Apollo. Particular attention was paid to display consoles, data processing systems, and communications requirements.[55] Displays were a crucial component, as they provided the interface between mission personnel and the systems, and they needed to convey information as quickly as possible so that a console operator could react to the data. Philco determined, out of numerous display formats such as text, graphs, diagrams, and clocks, that alphanumeric text would be optimal in most situations. Drawings, however, were determined to be more effective for displaying flight paths and maps as, although "written language is now one of man's most indispensable tools of communication, it is not necessarily the simplest or most efficient means of representing thoughts."[56] Designers aspired to be as flexible as possible with displays while also staying within a reasonable budget.[57]

A second major decision with regard to the display system was the *amount* of information that should be shown on console screens, as the human eye can only observe so much data at one time. Thirdly, Philco considered what information should be visible on the group displays at the front of the room, which were ten feet high and totaled 60 feet in width, and to what extent this information should replicate or supplement data available at consoles.[58] The Philco team thought that the group display was advantageous for a number of reasons, including allowing the group to coordinate its efforts efficiently, reducing the amount of equipment needed, providing operational reliability through its redundant nature, and providing a feeling of continued participation to temporarily idle operators.[59] The console displays, however, also had their assets. These screens could display specific information needed by a particular user, and the displays could be changed without disrupting the work of others.[60] Every decision was considered from the standpoint of guaranteeing mission success.

Communications was another consideration for ensuring space triumphs. Colonel Charles Abbitt had spent a portion of his US Air Force career as the DoD chief who coordinated the Mercury missions. In 1963, a flight surgeon grounded him for glaucoma in both eyes, and Abbitt applied for disability retirement at the age of 43. The Air Force only offered 30% of his retirement package, so when Abbitt visited LaBerge in Houston and was offered a job, he took it. His new position was manager of the Ground Operations Support System (GOSS) unification project for PHO, pending his retirement from the Air Force.[61] Abbitt's assignment as manager of the GOSS project was to maintain successful communication with the different actors involved in a spaceflight. These players included astronauts aboard spacecraft, as well as operators at worldwide tracking stations, launch facilities, and launch and recovery control complexes.[62] These spaces would be integrated by a communications network, with MCC serving as the focal point.

The arrangement of these systems required consensus between the various contractors involved. According to Abbitt, there was "much bickering" between Univac (the communications contractor), IBM (the computer contractor), and Philco (the lead contractor) about whether or not the center would be ready to control Gemini 4. Philco wanted to err on the side of caution, but Chris Kraft decided to make the center prime—that is, the primary control space—for Gemini 4. The mission was a success, especially because it included an American astronaut's first spacewalk.[63] LaBerge recalled that Abbitt did an excellent job of making the various contractors "mesh in a fruitful way."[64] Functioning together, display, communications, and data monitoring systems resulted in a holistic command center. Philco, however, modestly stated that the prime function of Mission Control was simply technical management, as "actual control of the manned spacecraft … rests ultimately with the astronauts."[65]

This does not diminish the value of Mission Control, however, as the center personnel needed to be able to predict all possible contingencies and provide solutions in the event that plans changed or equipment malfunctioned. If, for example, the spacecraft crew were responsible for rendezvous with another vehicle, it was still the job of ground support to "provide the crew with the necessary information regarding the status and attitude of the target vehicle, and the required maneuvers necessary to effect docking."[66] Along with this responsibility, Philco listed almost 60 explicit tasks that Mission Control must monitor and complete during a spaceflight mission. The design of the control center made these tasks possible.

Operations

The Gemini program may be regarded as an intermediary set of missions in which tasks that would be vital to Apollo, such as rendezvous between two orbiting vehicles, docking of spacecraft, and spacewalking were proven feasible. Yet it was also an essential program in its own right. Philco realized that the engineering feats of Gemini were not any less important than the over-arching political aim of NASA's organizational agenda: "Establish the U.S.A. as the first nation to achieve manned lunar landing and return (alive)."[67]

In order to accomplish this goal, administrators and technicians at Philco knew that the system needed both to cater to the space program and be mission specific, while also having a flexible architecture that would enable troubleshooting and on-the-fly fixes. Philco created an information flow plan to support the Apollo missions, based on NASA-expressed mission concepts. As in its assessment of Gemini, Philco asserted that the primary function of Mission Control was to "give as much responsibility as possible to the astronauts and the on-board systems" while remaining alert and ready to support the astronauts from the ground station.[68] MCC was labeled a "major information source" for the completion of a mission. The MCC computer provided the ability to generate information based on tracking and navigation data from a spacecraft (or ephemeris, which is a table of coordinates of an orbiting body tabulated at constant intervals in time). This data would be sent to the Flight Dynamics Officer and other crew members to enable them to make mission-crucial recommendations, such as maneuver thrust, which was used to orient the vehicle.[69] This example illustrates that MCC was a dynamic space whose design was created and implemented with almost every possible contingency considered. The Philco team's integration of display, communication, and data-processing technologies within MCC made a manned mission to the Moon possible.

In March 1965, Mission Control came online to serve as a backup for the Gemini 3 mission. In June 1965, MCC-H became the primary control center for all manned NASA flights. Kraft was satisfied when the space was completed, noting that "[t]he Houston center was spacious, the computers were faster and had much more capacity, the modern intercom system worked, and we were surrounded by support rooms where bright young systems people kept us supplied with every detail we requested. The words *control center* now encompassed all of it."[70] The design had basis in control centers of the past, but its high-tech components had necessitated novel interior architecture. While worldwide communications had been pioneered by the DoD in construction of the North American Air Defense Command and DEW Line radar defense systems, most of this work was classified, so little experience of those systems was available to those who designed NASA's control center.

These types of innovations were left to NASA and their contractors. According to the center's official history, "Human spaceflight 'drove' a reformation and near revolution in the civilian sector of communications and computer technology."[71] Ford Motor Company recalled its accomplishment proudly: "The project transformed science fiction into reality, because it meant that manned space activities would be conducted with full 'Earth Control'—a big leap at the time."[72] NASA executive James Satterfield asserted that Philco's ability to complete the contract was due to LaBerge's acumen as a technical administrator. Satterfield recalled that LaBerge "was a very smooth talker and a very competent technical person. I believe he could sell anybody anything if he set his mind it."[73]

This Mission Control Room has been called the "most highly automated information correlation center in existence," because of the vast amount of information it received, organized, and displayed. Data included the heartbeats of astronauts, spacesuit temperatures, and almost 300 other types of information related to spaceflight.[74] In 1965, Philco reported that MCC housed the largest assembly of television switching equipment in the world—larger even than commercial studios in New York City—as well as the "largest solid-state switching matrices of 20 megacycle bandwidth." This system was driven by more than 1100 cabinets of electronics equipment, 140 command consoles, 136 television cameras, and 384 television receivers. According to Gene Kranz, "This room [was] bathed in this blue-gray light that you get from the screen, so it's sort of almost like you see in the movies kind of thing."[75] Ten thousand miles of wire connected this behemoth, with more than two million wire connections. All of this construction resulted in a highly sophisticated system that was capable of storing high-density, real-time data on server computers, which was then accessible to many different users via primitive client software.[76]

Philco developed a TV matrix that enabled operators to call one of up to 20 television stations for display on their console.[77] John "Jack" Garman, who advised flight controllers during the Apollo missions and later served as a NASA executive, recalled the awe that the space inspired:

> So when you walked into mission control … what you saw down on the first floor, was all these big IBM mainframes with the spinning tape drives and the lights blinking and all that … It doesn't mean anything to anybody today. That's how computers work today, right? But in those days, if you spent your life in front of a keyboard typing punch cards and when the computer ran, you got it back on paper, to be able to see things happening on the screen in real time was absolutely awesome, particularly if you knew anything about computers.[78]

Another key feature of MCC was redundancy. Every piece of equipment in the room had a spare or auxiliary. RTCC housed five IBM 7094 computers, of which two were needed to coordinate a mission, and the remaining three could either operate as redundant spares or be used for training for future missions while the current one was underway.[79] The electrical power supply was backed up by diesel-driven generators, in the event that the center lost electricity from Houston Light and Power.[80] The entire system was state of the art. However, even beyond the high-tech equipment and dazzling displays, the Mission Control Room exuded an intangible spirit that the work being conducted in this space was important. In Kranz's words:

> [It is] the room's atmosphere, it's the smell of the room, and you can tell people have been in there for a long period of time. There's enough stale pizza hanging around and stale sandwiches and the wastebaskets are full. You can smell the coffee that's been burned into the hot plate in there. But you also get this feeling that this is a place something's going to happen at. I mean, this is a place sort of like the docks where Columbus left, you know, when he sailed off to America or on the beaches when he came on landing.[81]

The space also probably held an odor of stale cigarettes, as smoking was not banned until 1987.[82]

NASA scientist James Head III recalled that during missions, everyone in the control center was pumped up on adrenaline and oblivious to the outside world. "It's like, there are just no windows," he said, "so you can be in there for days and not know what's going on [outside]."[83] Unfortunately, there was unequal access to this awe-inspiring space. Women were not allowed out on the floor of the Mission Control Operations Room. Engineer Jeanne Crews recalled that she "spent many times on the Skylab experiments in the back rooms, and then if I'd walk in the elevator, there would be comments by the two people I referred to, like, 'Well, it's certainly good we keep women out of the Mission Control.'"[84] Nor were the systems perfect: operators constantly revised the room's features. For example, one NASA official recalled:

> We had problems with people leaning over the consoles and touching buttons and switches, and so we wanted a cover on the command switches. We had a good idea, but people didn't know how to do it, so guys would

> take the plastic home and cook them in the oven, and that's how we made the first ones. There was a lot of creativity by people like that.[85]

Further, Mission Control used a pneumatic tube system to carry hardcopy messages and printouts of the television displays.[86] Hundreds of messages littered the floor after hectic shifts. As Kranz remembered it, after one such day, flight controller officer John Llewellyn, "a former Marine, stood up, stretched, and in a voice for all to hear declared: 'I think I am back in the trenches again with my fire control team, surrounded by empty 105 howitzer canisters.'"[87] Despite these exceptions, MCC was as technologically state of the art as possible, and its innovative qualities cannot be exaggerated. It not only served to facilitate NASA's spaceflight goals, but its design aesthetic added an archetypal control center space to America's cultural consciousness, as well as bolstered the prestige of the space program.

Due to television and press coverage, Americans came to identify Mission Control with the Gemini and Apollo spaceflight accomplishments between 1965 and 1972. Johnson Space Center historian Jennifer Ross-Nazzal rightly noted: "One of the most popular images was taken after the Apollo 11 crew safely returned home and features flight controllers celebrating the conclusion of the first successful mission to the moon."[88] After years of coming in second to the USSR, this space came to symbolize American technological and political might during in the Cold War. NASA's sociopolitical purpose was "civil offense." The space agency attacked the Soviet Union with each successful mission in the war for technological supremacy, world recognition, and economic dominance. At the same time, stable and elevated taxpayer support provided a return on investment (Figs. 5.2, 5.3).

Conclusion

In 2011, NASA renamed Johnson Space Center's Building 30 the Christopher C. Kraft Mission Control Center. Then current JSC Director Michael Coats lauded Kraft in a speech: "He is a space pioneer without whom we'd never have heard those historic words on the surface of the moon, 'Houston, Tranquility base here. The Eagle has landed.' Those words effectively put Houston, and this building behind us, on the intergalactic map forever."[89] Kranz similarly acknowledged Kraft's contributions:

Fig. 5.2 View of activity at the flight director's console in the Mission Operations Control Room in the Mission Control Center, Building 30, on the first day of the Apollo 10 lunar orbit mission. Seated are Gerald D. Griffin (foreground) and Glynn S. Lunney, Shift 1 (Black Team) flight directors. Milton L. Windler, standing behind them, is the flight director of Shift 2 (Maroon Team). In the center background, standing, is Dr. Christopher C. Kraft, Jr., MSC Director of Flight Operations (NASA, image number S69-34038, public domain). Available at https://spaceflight.nasa.gov/gallery/images/apollo/apollo10/html/s69-34038.html

> I think Kraft's name, Christopher Columbus, was entirely appropriate for this guy because he was the pioneer in Mission Control. He launched each one of the Mercury missions. But most important, he was the mentor, the teacher, the tutor for this first generation of young people who became known as Mission Controllers. He set the mold for everything that would be done thereafter; and in particular, he set the mode for the flight director and the flight director being able to take any action necessary for crew safety and mission success.[90]

Kraft certainly deserves the praise lavished upon him for directing NASA operations and landing a man on the Moon, among many other accomplishments. NASA, however, also owes debts to the contractors who

Fig. 5.3 Newly arrived Expedition 33 crew members, Russian cosmonaut Oleg Novitskiy, front left, NASA astronaut Kevin Ford, front center, and Russian cosmonaut Evgeny Tarelkin, front right, are seen on a screen at the Russian Mission Control Center in Korolev, Russia, shortly after the three joined Flight Engineer Aki Hoshide of the Japan Aerospace Exploration Agency, back left, Expedition 33 Commander Sunita Williams of NASA, back center, and Yuri Malenchenko of the Russian Federal Space Agency, on October 25, 2012 (NASA/Bill Ingalls, public domain). Available at https://www.nasa.gov/mission_pages/station/multimedia/gallery/201210250004hq.html

imagined and implemented the high-tech systems that made the feats of manned spaceflight possible.

By the 1990s, the once-revolutionary technology that supported Mission Control was outdated to the point that the entire center needed to be redesigned. In July 1995, a new Mission Control Center, which implemented the latest generation of cutting-edge technology, began operations. One of the two Apollo-era MCCs was set aside as a national historical facility. It is currently on display at Space Center Houston, located in the Visitor's Center of Johnson Space Center.

Notes

1. One exception is the recently published Michael Peter Johnson, *Mission Control: Inventing the Groundwork of Spaceflight* (Gainesville: University Press of Florida, 2015).
2. For the sake of readability, I use "Philco" to refer to the primary contractor in the design of NASA's Mission Control, even though this designation is not completely accurate. Philco was an electronics company that was acquired by Ford in 1961, leading to the new name of Philco-Ford. Soon after, the Western Development Laboratory was created as a division within Philco-Ford (Philco-Ford WDL) that fulfilled Ford's desire to win aerospace-related contracts in the 1960s. When NASA contracted Philco-Ford WDL to design the Mission Control Center in Houston, a subdivision of Philco-Ford was created to support the project—Philco Houston Operations—although documentation for the initial design refers to the contractor as Philco-Ford WDL. To further complicate the business history, in the late 1970s, Philco-Ford and its subdivisions were renamed Ford Aerospace. Philco employee of almost 20 years (1965–1983) John Abbitt articulated the confusion in his memoirs: "In 1975 the corporation changed its name to Aeronutronic Ford and in 1976 to Ford Aerospace & Communications Corporation (FACC). Philco Houston Operations (PHO) was transferred from WDL to the Engineering Services Division, and we became Space Information Systems Operations (SISO), replacing the PHO name but still belonging to Ford Motor Company!!" He did, however, also note that "During all these management name changes the local operation was essentially autonomous, while fitting into the overall financial structure of the corporate staff. Little notice of these changes was required by NASA (our customer), at least during my tenure." Unpublished memoirs, *Life and Times of Colonel Charles W. Abbitt, United States Air Force, Retired* (1 March 2001): 30, 21.
3. This chapter does not privilege the "genius" architect or scientist as the creator of command centers, and rightfully so: in the age of Big Science, the lone inventor had largely disappeared. More often, teams of people worked together to create new technologies, and that was certainly the case for the massive technology of the command center. This remains, however, a story about people.
4. The aerospace industry's dependence on the federal government has been examined by a number of authors. See Ann Markusen, et al., *The Rise of the Gunbelt: The Military Remapping of Industrial America* (New York: Oxford University Press, 1991).

5. Kraft, however, credited the Philco and IBM teams for the design of Mission Control Center in Houston. Henry C. Dethloff, *Suddenly, Tomorrow Came: A History of the Johnson Space Center* (Washington, DC: NASA SP-4307, 1993): 86.
6. Interview with James M. Satterfield by Robert B. Merrifield, 13 March 1968, p. 5. Courtesy Philip La Berge; Chris Kraft, *Flight: My Life in Mission Control* (New York: Plume, 2002), 87.
7. Kraft, *Flight*, 124.
8. Ibid., 100; Ground control of the vehicle was not possible in the Mercury Control Center. Once the capsule was launched, ground control could only communicate with the vessel. *Suddenly*, 55.
9. Ibid., 100–101.
10. Ibid., 102.
11. Ibid., 103.
12. Ibid., 133.
13. Gene Kranz, *Failure is Not an Option: Mission Control From Mercury to Apollo 13 and Beyond* (New York: Simon & Schuster, 2009), 22.
14. NASA Johnson Space Center Oral History Project, Oral History Transcript, Glynn S. Lunney interviewed by Roy Neal, Houston, Texas, March 9, 1998, 12-26–12-27.
15. Kranz, *Failure is Not an Option*, 70.
16. Dethloff, *Suddenly, Tomorrow Came*, 85.
17. Lunney oral history, 12–11.
18. NASA Johnson Space Center Oral History Project, Oral History Transcript, T. Rodney "Rod" Loe interviewed by Carol L. Butler, Houston, Texas, November 30, 2001, pp. 1–2.
19. Kraft, *Flight*, 144.
20. Dethloff, *Suddenly, Tomorrow Came*, 85.
21. Dethloff, *Suddenly, Tomorrow Came*, 36, 38.
22. Dethloff, *Suddenly, Tomorrow Came*, 41; Kranz, *Failure is Not an Option*, 81.
23. Stephen B. Oates, "NASA's Manned Spacecraft Center at Houston, Texas," *The Southwestern Historical Quarterly*. 67, No. 3 (January 1964): 370.
24. Dethloff, *Suddenly, Tomorrow Came*, 33, 48.
25. NASA Johnson Space Center Oral History Project, Oral History Transcript, Eugene F. Kranz interviewed by Roy Neal, Houston, Texas, March 19, 1998: 12–11; 12–14.
26. Kraft, *Flight*, 171.
27. "Real Property Record – Buildings," from "MCC History Notes.pdf," Courtesy JSC History Office.
28. Dethloff, *Suddenly, Tomorrow Came*, 48.

29. "MCC: Mission Control Center," from "MCC History Notes.pdf," Courtesy JSC History Office.
30. "NASA Facts: Mission Control Center," from "MCC History Notes.pdf," Courtesy JSC History Office.
31. In NASA and Philco documentation, it is also referred to as the Integrated Mission Control Center (IMCC). The name is shortened for both brevity and adherence to common usage.
32. Letter from Robert D. Legler to John Getter titled "Responses to Questions About Historical Mission Control," April 7, 1997, from "Facts About MCC.pdf," Courtesy JSC History Office.
33. Transcript of oral history interview with Walter LaBerge, conducted at behest of NASA, 31 July 1968. LaBerge edited the transcript and sent it to Robert B. Merrified at the Manned Spacecraft Center on December 4, 1968, p. 1. Courtesy Philip LaBerge.
34. Wikipedia entry: "Philco," accessed November 2, 2012 at URL: http://en.wikipedia.org/wiki/Philco. This information is corroborated by another website: Carlos A. Altgelt, "A Brief History of Philco," accessed November 2, 2012, at URL: http://www.oldradio.com/archives/hardware/philco.htm; early history available in William Balderson, *"Philco": Autobiography of Progress* (New York: The Newcomen Society, 1954). For a lengthier acquisition history, while Philco was sold to General Telephone and Electric in 1974, the aerospace component of Philco-Ford, which was responsible for the design of Mission Control, became Aeronutronic Ford Corporation in 1976, then Ford Aerospace the following year, and was eventually sold to the Loral Corporation in 1990. In 1963, FMC folded its Aeronutronic Company into Philco; the larger company was renamed Philco-Ford in 1966.
35. *For My Children*, the unpublished memoirs of Walter LaBerge (1996), 131. Courtesy Philip LaBerge.
36. Ray Loree, "MCC Development History," 1990, p. 1, from "Ray Loree MCC History.pdf," Courtesy JSC History Office; "Contractual History of Major Implementation and Operations Milestones," January 10, 1985, from "Contractual MCC History.pdf," Courtesy JSC History Office.
37. Press Release, Ford Motor Company, "Philco Corp. – Mission Control Center in Houston – Dr. W. B. LaBerge," no date, Ford Motor Company LaBerge Presentation press release no date.pdf. Courtesy Ford Motor Company Archives.
38. Press Release, Philco Corporation News Department, March 17, 1965, Philco Mission Control Center Facts and Figures press release 3-17-1965.pdf, Courtesy Ford Motor Company Archives.
39. "Philco-Ford," accessed November 2, 2012 at URL: http://davidszondy.com/future/Living/ford_philco.htm

40. His journalistic inclinations never faded, however, as his prolific writing in later years attests. *For My Children*, 1. Courtesy Philip LaBerge.
41. This goes against conventional wisdom that the heyday for physicists began in and was sustained after the Manhattan Project. *For My Children*, 87. Courtesy Philip LaBerge.
42. Press Release, Philco Corporation News Department, March 17, 1965. Courtesy Ford Motor Company Archives.
43. *For My Children*, 132. Courtesy Philip LaBerge.
44. Ibid., 132.; Press Release, Philco Corporation News Department, March 17, 1965, Philco Mission Control Center Facts and Figures press release 3-17-1965.pdf, Courtesy Ford Motor Company Archives.
45. Transcript of oral history interview with Walter LaBerge, 12.
46. *For My Children*, 133.
47. Ibid., 135.
48. James Tomayko, "Chap. 8: Computers in mission control," in *Computers in Spaceflight: The NASA Experience*, an e-book prepared by NASA, available at URL: http://www.hq.nasa.gov/pao/History/computers/Ch8-1.html
49. Interview with James M. Satterfield by Robert B. Merrifield, March 13, 1968, 22. Courtesy Philip La Berge.
50. United States Patent US2722862 filed September 12, 1949; United States Patent US2923129 filed May 8, 1953; United States Patent US2917628 filed December 15, 1959.
51. Edward Jones, *Playing With Fire: Memoirs of a 1950s Rocket Science Pioneer*, 2011. Available at URL: https://sites.google.com/site/playingwithfirememoirs/title-page, accessed November 30, 2012.
52. Oral History of Floyd Lvamme, interviewed by John Hollar for the Computer History Museum, Mountain View, CA, October 18, 2001.
53. *For My Children*, 132.
54. Philco Western Development Laboratory, Facility Requirements and Criteria, Contract No. NAS-9-366, Design and Development Study for Manned Space Flight Operations Control and Support, WDL Technical Report E112–3, September 7, 1962, 2–2.
55. Philco Western Development Laboratory, IMCC Systems and Performance Requirements Specification, Contract No. NAS-9-366, WDL Technical Report E120, September 7, 1962: 1–1.
56. Ibid., 2.1.2–4.
57. Ibid., 5.1.2–2.
58. Press Release, Philco Corporation News Department, 17 March 1965, Courtesy Ford Motor Company Archives.
59. Philco Western Development Laboratory, IMCC Systems and Performance Requirements Specification, Contract No. NAS-9–366, WDL Technical Report E120, 7 September 1962: 5.1.2–7.

60. Ibid., 5.1.2., 7–8.
61. Unpublished memoirs, *Life and Times of Colonel Charles W. Abbitt, United States Air Force, Retired*, March 1, 2001, 19–20. Courtesy Lawrence Reeves.
62. Ibid., 22.
63. Ibid., 24.
64. Transcript of oral history interview with Walter LaBerge, conducted at behest of NASA, 31 July 1968. LaBerge edited the transcript and sent it to Robert B. Merrified at the Manned Spacecraft Center on December 4, 1968, p. 1. Courtesy Philip LaBerge.
65. Philco Western Development Laboratory, Information Flow Plan (Gemini Rendezvous Operation), Contract No. NAS-9-366, WDL Technical Report E114–2, July 9, 1962: 1.2–1.
66. Ibid., 2.2.11–2.
67. Philco Western Development Laboratory, IMCC Systems and Performance Requirements Specification, Contract No. NAS-9-366, WDL Technical Report E120, September 7, 1962: 5.1.2., 7–8.
68. Philco Western Development Laboratory, Information Flow Plan (Manned Apollo Mission), Contract No. NAS-9-366, WDL Technical Report E121, August 21, 1962: 3.1–1.
69. Ibid., 4.4.4–1.
70. Kraft, *Flight*, 219.
71. Dethloff, *Suddenly, Tomorrow Came*, 83.
72. "Company Milestones: Our Role in Putting a Man on the Moon," on the Ford Motor Company website, accessed November 2, 2012, at URL: http://corporate.ford.com/our-company/heritage/company-milestones-news-detail/683-nasa-mission-control.
73. Interview with James M. Satterfield by Robert B. Merrifield, March 13, 1968. Courtesy Philip La Berge.
74. Press Release, Ford Motor Company, "Philco Corp. – Mission Control Center in Houston – Dr. W. B. LaBerge," no date, Ford Motor Company LaBerge Presentation press release no date.pdf. Courtesy Ford Motor Company Archives.
75. NASA Johnson Space Center Oral History Project, Oral History 2 Transcript, Eugene F. Kranz interviewed by Rebecca Wright, Houston, Texas, January 8, 1999, 13–37.
76. Press Release, Philco Corporation News Department, March 17, 1965, Philco Mission Control Center Facts and Figures press release 3-17-1965.pdf, Courtesy Ford Motor Company Archives.
77. Johnson Space Center Oral History Project Oral History Transcript, Henry E. "Pete" Clements interview by Carol Butler, Melbourne, Florida, August 31, 1998, 12–25; According to NASA executive James

Satterfield, the initial system of projection and television screens had been developed by Finsky, Fisher & Moore in California for the Air Defense Command Headquarters in Colorado for displaying tactical data. Philco modified the system to work at Mission Control. I cannot substantiate this claim with other sources. See interview with James M. Satterfield by Robert B. Merrifield, March 13, 1968, 20–21. Courtesy Philip LaBerge.

78. NASA Johnson Space Center Oral History Project, Oral History Transcript, John R. "Jack" Garman interviewed by Kevin M. Rusnak, Houston, Texas, March 27, 2001, 14.
79. Press Release, Philco Corporation News Department, March 17, 1965, Philco Mission Control Center press release 3-17-1965.pdf. Courtesy Ford Motor Company Archives.
80. NASA Johnson Space Center Oral History Project, Oral History Transcript, Dennis E. Fielder interviewed by Carol Butler, Houston, Texas, July 6, 2000, 29.
81. NASA Johnson Space Center Oral History Project, Oral History 2 Transcript, Eugene F. Kranz interviewed by Rebecca Wright, Houston, Texas, January 8, 1999, 13–38
82. Letter from Robert D. Legler to John Getter titled "Responses to Questions About Historical Mission Control," April 7, 1997, from "Facts About MCC.pdf," Courtesy JSC History Office.
83. NASA Johnson Space Center Oral History Project, Oral History Transcript, James W. Head, III interviewed by Rebecca Wright, Providence, Rhode Island, June 6, 2002, 35.
84. NASA Johnson Space Center Oral History Project, Oral History Transcript, Jeanne L. Crews interviewed by Rebecca Wright, Satellite Beach, Florida, August 6, 2007, 17.
85. NASA Johnson Space Center Oral History Project, Oral History Transcript, Jones W. "Joe" Roach interviewed by Carol Butler, Houston, Texas, January 24, 2000, 12–4.
86. Interview with James M. Satterfield by Robert B. Merrifield, March 13, 1968, 26, Courtesy Philip La Berge.
87. Kranz, *Failure is Not an Option*, 141.
88. Jennifer Ross-Nazzal, "Landmarks at Johnson Space Center," *Houston History* 6/1 (Fall 2008): 45.
89. "NASA Names Mission Control for Legendary Flight Director Christopher Kraft," accessed November 2, 2012 at URL: http://www.nasa.gov/mission_pages/shuttle/behindscenes/kraft_mcc.html.
90. NASA Johnson Space Center Oral History Project, Oral History Transcript, Eugene F. Kranz interviewed by Roy Neal, Houston, Texas, April 28, 1999: 14-46–14-47.

CHAPTER 6

Lessons of Landsat: From Experimental Program to Commercial Land Imaging, 1969–1989

Brian Jirout

In 1969, newly elected President Richard Nixon gave a speech at the United Nations (UN) promising to share the benefits of space with the world.[1] Specifically, he mentioned Earth resource survey satellites capable of monitoring natural resources from space and promised to share data of this sort with the global community. The announcement received a somewhat mixed reaction from member states, who expressed concern that the USA might use the data for its own economic gain. The US government worked to assuage such anxiety by expressing "the view that the principles embodied in the Outer Space Treaty clearly apply to the activities of states in remote sensing of the earth by satellites," and that the USA sought to "facilitate the maximum international availability and effective utilization of data."[2] From this point of view, ubiquitous data availability at an affordable price was in the interest of all potential users of Earth resource surveying.

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By 1972, the USA had launched the first civilian land remote sensing satellite, the Earth Resources Technology Satellite, later renamed Landsat 1. The satellite was a highly innovative apparatus that, as the first of its kind, offered a wide range of applications for environmental monitoring and data gathering. In a 2013 report, the US Geological Survey (USGS) identified nine broad categories of applications, among them agriculture, education, environmental sciences, and energy.[3] Landsat carried two sensors, a return beam vidicon and an experimental multispectral scanner (MSS). Landsat 4 carried an advanced MSS, the Thematic Mapper, which had improved spectral coverage. A typical Landsat image captured a 185 square kilometer field of view across several spectral bands, which allowed users to view the Earth beyond the human eye's capability. This became Landsat's greatest innovation: the satellite provided a new perspective that contributed to numerous studies in the environmental sciences, agriculture, land use planning, and energy development, among others. Innovation lies within application, since Landsat imagery enabled users to address environmental concerns and natural resource development. However, in order for users to apply Landsat images to terrestrial problems, openly available and affordable data had to be accessible to all potential users.

NASA and USGS also built partnerships with other federal agencies and international collaborators to broaden data availability to users. The federal government also aimed to make data as widely available as possible and eventually sought to commercialize the program through an agreement with the private sector. This was the first such arrangement to commercialize an environmental application satellite. These conditions make Landsat a ripe case for understanding the history of innovation at NASA through three key lessons.

The first lesson is that although government-granted monopolies became useful for delivering services and scientific data, it was not an effective mechanism for promoting innovation and commercialization. In this case, cost-prohibitive data pricing is the culprit. Second, Landsat teaches us that innovation and commercialization can be a highly political process, rather than a product. Third, innovation is different than commercialization, since Landsat data exhibits the qualities of a public good rather than a private commodity, which complicates profitability. In addition, the risks of commercializing Landsat data increased with the ability of innovation proponents to deny reality, in this case of a robust market for land remote sensing data.

This chapter traces Landsat's history from an experimental program under NASA and later USGS to a program operated by the National Oceanic and Atmospheric Administration, which contracted the program out to the private sector. I argue that the availability of Landsat data fluctuated from 1972 until roughly 1978, when data became available to many users at affordable pricing, but by 1984 Landsat was a commercial entity and began to stifle innovations in Landsat data application.

Early Landsat Years, 1966–1978

The idea of an Earth resources satellite did not originate at NASA. Rather, the Department of the Interior (DoI) took the space agency by surprise on September 21, 1966, when Secretary Stewart Udall announced the Earth Resources Observation Satellites program. The program, "aimed at gathering facts about the natural resources of the earth from earth-orbiting satellites carrying sophisticated remote sensing instruments," would "provide data useful to civilian agencies of the Government such as the Department of Agriculture (USDA) who are concerned with many facets of our natural resources."[4] Even though NASA carried out a number of feasibility studies with USGS to explore the possibility of such a satellite, DoI "became impatient with NASA's lack of progress toward defining a satellite system."[5] Dr. William Pecora, a geologist by training, received his PhD from Harvard University and eventually became Director of USGS in 1964. Immediately he began advocating for a remote sensing program capable of gathering information about Earth resources. Pecora and two of his USGS scientist colleagues, Charles Robinove and William Fischer, urged Secretary Udall to act boldly on the Earth resources satellite issue. Glenn Landis, former Chief of the Earth Resources Observation Systems Data Center (EROS), said "they [Robinove, Fischer, and Pecora] convinced Udall to basically twist NASA's arm … it was a total bluff. But it worked!"[6] The gambit by USGS prompted a long partnership with NASA which precipitated serious research and development resulting in Earth Resources Technology Satellite A (ERTS-A, later renamed Landsat 1; Fig. 6.1). In a 1969 letter from Pecora to NASA, he expressed the Survey's support of Landsat as "a means of acquiring on a national or worldwide scale data specifically designed to be useful for the widest variety of resource-related activities."[7] Alongside USGS, USDA also partnered with NASA to encourage a civil remote sensing program.

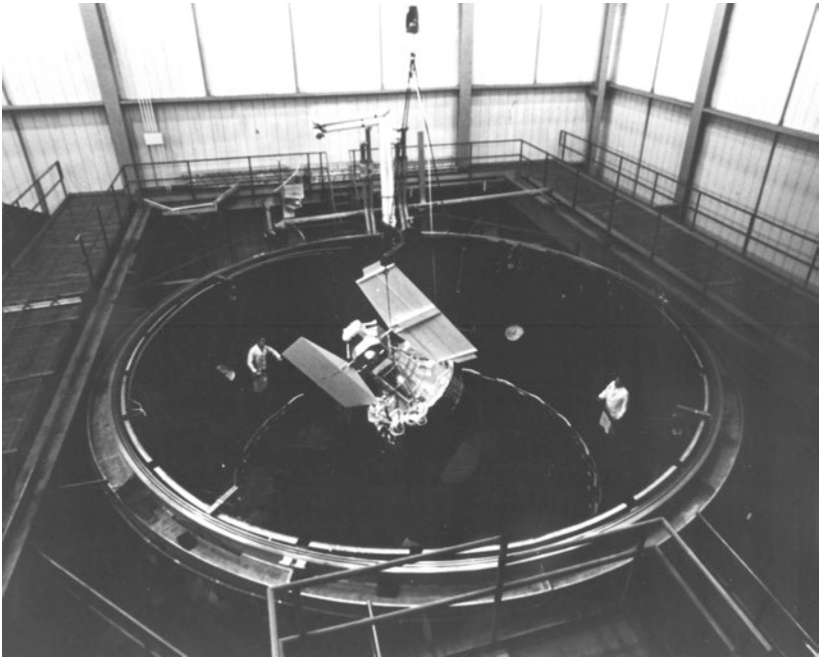

Fig. 6.1 Landsat 1 in development in the early 1970s. (NASA, image number 71-HC-973, public domain. (Available at https://www.flickr.com/photos/nasacommons/9467415896/in/album-72157634968559381/))

NASA, USGS, and USDA, with advice from the National Academy of Sciences, "initiated research to investigate the feasibility of assessing agricultural conditions with automated remote sensing techniques."[8] Pecora and Dr. Archibald Park of USDA committed their institutions to supporting the Landsat mission and using its data. Park served as head of remote sensing research and made recommendations to NASA for Landsat specifications, in particular on resolutions necessary to view vegetation. NASA responded by offering grants for further study of agricultural applications. It awarded a grant to Purdue University to establish the Laboratory for Agricultural Remote Sensing (LARS) in 1966. NASA, with the influence of USDA specifications, decided to include a multispectral scanner on the Landsat 1 platform, which it built in 1967 and 1968. Simultaneously, LARS assembled a data processing system capable of identifying crops, namely wheat and corn, from the multispectral scanner data.

During these years, NASA, LARS, and USDA flew airplanes over the Midwest to test these scanners. NASA successfully used the Apollo 9 platform to simulate how the scanner would operate in space in 1969.[9] President Nixon's aforementioned speech to the UN that year generated widespread interest in the program. Over the next three years, NASA built the first Landsat satellite, explored its potential for applications, and prepared to make its data available.

NASA launched Landsat 1 from Vandenburg Air Force Base on July 29, 1972. From the moment the agency received the first images, new applications emerged in agriculture, hydrology, and geology. NASA partnered with USDA to use Landsat data to predict wheat crop growth. The Large Area Crop Inventory Experiment (LACIE) became the first major project involving Landsat data. It related to Landsat data collected over time, tracking the maturation of wheat in the USA, Canada, and the Soviet Union, as well as weather data such as average rainfall and temperature, plus soil sampling. From these variables, NASA's Johnson Space Center and USDA's Agricultural Stabilization and Conservation Service scientists formulated an algorithm that predicted wheat growth. The experiment fell well short of becoming a global crop prediction formula, but it proved that Landsat was capable of surveying natural resources from space; this success led to additional experimentation and improvement of both Landsat sensors and data processing.[10]

NASA also forged a partnership with the US Agency for International Development (USAID), not only to make Landsat data available abroad, but also to encourage innovative applications of imagery to environmental issues around the world. In mid-1974, NASA and USAID and their contractor, Environmental Research Institute of Michigan (ERIM), opened a call for "Competitive Grants Program to Foster Broader Utilization of ERTS Data for Development Purposes." The USAID Grant Panel, which included members from USAID, NASA, ERIM, USGS, and another contractor, Systems Planning Corporation, received 31 proposals from mostly foreign governments and universities, and selected 9 divided among Africa, Asia, and South America. Lesotho won a grant to investigate "snowfall patterns in Lesotho in order to obtain previously inaccessible water run-off data of importance to the agricultural development of the country."[11] The University of Botswana, Lesotho, and Swaziland's Department of Biology carried out the project with $18,000 in USAID funds and ERTS technical training from NASA and USGS, and produced hydrological maps that indexed drainage and soil types in addition to vegetation surveys of the entire country. This application allowed Basotho scientists to understand the hydrological patterns of the landscape, which informed agriculturalists as to which areas were most prone to flooding during snow melts.

In addition to sending data and expertise abroad, NASA also encouraged innovation by forming partnerships with foreign space agencies to receive Landsat data directly. NASA and USGS formed partnerships with other countries to make data available through data-receiving ground stations. The Canadian government approached NASA first with a proposal to receive Landsat data at the newly established Canadian Centre for Remote Sensing (CCRS) near Ottawa. NASA's Office of International Affairs agreed to allow CCRS to receive and distribute Landsat data if it obtained the equipment to do so, and agreed to a nondiscriminatory data access policy. CCRS built antennas and developed its own data processing units; these were beyond NASA specifications and had superior turnaround time to those at NASA's Goddard Spaceflight Center.[12] Canada became the first country to build a ground station, setting the precedent for others to follow. Throughout the 1970s, the European Space Agency, Geoscience Australia, Brazil's Instituto Nacional de Pesquisas Espaciais, and the South African National Space Agency each negotiated a Memorandum of Understanding with NASA to also develop ground stations that followed the Canadian model. Over time, 34 ground stations received data downlinks from Landsat.[13] Foreign ground station operators, called international cooperators, acquired the necessary equipment, negotiated with NASA and USGS to receive Landsat downlinks, and paid an annual $200,000 operating fee, but were allowed to distribute data freely. Ground stations abroad inspired new applications, such as the Brazilian effort to map the Amazon river basin and deforestation.[14] In Canada, CCRS provided data to the Canadian Hydrological Service in 1976, which revealed a previously uncharted island. After a run-in with a polar bear and some Canadian Parliamentary debate, Dr. Frank Hall of the Hydrological Service added 68 square kilometers to Canada and named the new landform Landsat Island![15]

These partnerships, inspired by Landsat use, led to innovations in remote sensing. The White House took notice of Landsat's experimental success and formulated a new plan for Landsat operations in 1978. The Carter and Reagan Administrations exercised stronger budgetary constraint, which exacted a toll on Landsat. As an experimental program, Landsat remained a NASA project, but in November 1979 the Carter

Administration turned it over to the National Oceanic and Atmospheric Administration (NOAA). When the Reagan Administration entered the White House, it pressed NOAA to commercialize Landsat, a move that eventually stifled innovation.

Commercialization and the Failure of Innovation

By 1978, the federal government began to approach Landsat data differently. To many policymakers, it appeared that Landsat was no longer experimental, and was instead fully operational. At this juncture, Landsat and the data it produced evolved from an experimental, scientific project into a commercially viable program. President Jimmy Carter brought sweeping changes to the Landsat program by issuing three Presidential Directives. The first, in May 1978, emphasized maintaining American leadership in remote sensing and data continuity, as well as encouraging "domestic commercial exploitation of space capabilities and systems for economic benefit."[16] The second, PD-42, released on October 11, 1978, placed Landsat and weather and ocean remote sensing satellites on a timeline for commercialization which would be "addressed in the FY 1980 budget review" and would "examine approaches to permit flexibility to best meet the appropriate technology mix, organizational arrangements, and potential to involve the private sector."[17] President Carter also sought integration among the satellite programs. The final and most significant Presidential Directive, entitled "Civil Operational Remote Sensing," came a year later, on November 16, 1979. It brought two major changes to Landsat. First, it turned Landsat management over from NASA to NOAA. The move mirrored the transfer of the TIROS weather satellites from NASA to the Environmental Science Service Administration. The second change was to set Landsat's commercialization in motion. The directive stated that the White House's "goal is the eventual operation by the private sector of our civil land remote sensing activities."[18] NOAA managed Landsat until the Department of Commerce formulated what type of arrangement Landsat would become commercially.[19] By late 1979, NASA's role in the Landsat program had diminished as its partners began to assume satellite operations.

In contrast, commercialization stifled Landsat data use and innovation. While Landsat embarked on the road to becoming a commercial viability, NASA and the White House sought to maintain low-cost innovation with new satellites and data viability.

The Reagan Administration's Vision for Landsat

President Ronald Reagan took the oath of office on January 20, 1981 and within a few months brought rapid changes to the Landsat program. Originally, Carter's FY 1982 budget "included $123.8 million for NOAA's initiation of the program in order to assure program continuity" as well as funds for research and development of Landsats 6 and 7 appropriated to NASA. Reagan, however, slashed the NOAA budget significantly and eliminated funding for Landsats 6 and 7 entirely.[20] For the new White House, the Landsat program was an enterprise to be developed entirely by the private sector. Reagan tasked the Office of Management and Budget (OMB) and Commerce with carrying out this directive. In February 1981, Reagan reorganized the presidency by setting up "Cabinet councils to serve as the formal bodies for debating and shaping the major policies of his Administration."[21] Since Landsat formally came under NOAA management, the newly formed Cabinet Council on Commerce and Trade (CCCT), headed by Secretary of Commerce Malcolm Baldrige, assumed the commercialization policy issue. OMB Director David Stockman encapsulated President Reagan's vision for the Landsat program by requesting that Baldrige encourage the CCCT to "[transfer] Landsat to the private sector *as soon as possible*."[22] What followed was six years of heated debate between Congress, the Executive Branch, industry, and users with regards to the reshaping of Landsat and its use entering the 1980s.

Baldrige also played a pivotal role in establishing two more groups that formulated Landsat commercialization policy. Within Commerce, Baldrige approved the formation of the Program Board for Civil Operational Land Remote Sensing from Space. The Board's goal was to coordinate federal efforts to manage Landsat on behalf of Commerce, which NOAA would implement.[23] Baldrige also formed the Land Remote Sensing Satellite Advisory Committee (LRSSA) to advise Commerce on Landsat data user requirements, data pricing, and private ownership issues.[24] This committee included 15 members from non-federal user communities, including state and local governments, the value-added service industry such as data analysis companies, university representatives, and potential investors from the aerospace industry.

The CCCT, Program Board, and LRSSA met between 1981 and 1984 to form a commercialization policy on behalf of Baldrige and Reagan. In 1981, NOAA and USGS operated Landsats 2 and 3 and maintained seven international ground stations. The government terminated Landsat 3's operation in 1983, but launched Landsat 4 in 1982 and Landsat 5 in 1984. Over the course of several years, these committees advised Commerce and Congress on how best to commercialize Landsats 4 and 5, encouraging later Landsats to be paid for by private operators, and also commercializing weather satellites.

NOAA's Call for Contractors in 1983

In March 1983, NOAA released its Request for Proposals (RFP) to solicit commercial operators of Landsat and weather satellites. The RFP signaled that, despite a lack of legislation, considerable opposition, and myriad unresolved policies, Landsat would become a commercial entity. Yet the NOAA RFP was less a mechanism for soliciting proposals, and more a political instrument meant to accelerate Landsat commercialization. The major issue that caused so much opposition was the effort by the Reagan Administration to commercialize Landsat and weather satellites simultaneously, which elicited strong opposition from the House of Representatives.

In line with Reagan's vision for Landsat, the White House charged Baldrige with soliciting commercial operators. Commerce did so by forming a Source Evaluation Board (SEB), headed by William P. Bishop of NOAA, in May 1983. Baldrige tasked this in-house group with both soliciting and evaluating proposals from private-sector parties who sought to operate Landsat and weather satellites, after having issued an RFP.[25] The RFP required that all potential operators be American, communicate directly with Commerce, abide by all relevant laws and regulations (such as the Export Administration Act, Arms Export Control Act, Sherman Anti-Trust Act, and so on), and ensure no employment conflict of interests. Furthermore, the RFP had three basic objectives: develop a commercial system based on Landsat, maintain US leadership in remote sensing, and foster economic benefits for private and public good.[26] In order to accomplish these objectives, NOAA sought an operator that could distribute data and data services, operate Landsats 4 and 5 throughout their lifetimes, and develop subsequent Landsats.

The RFP also presented a number of issues that complicated the commercialization process and it elicited strong resistance from the House of Representatives. First, the White House insisted that Landsat and weather satellites both commercialize, despite the aforementioned resistance. From March to November, the RFP went through numerous iterations, and a November 18, 1983 draft had cut all meteorological and oceanic satellites from its language, which had originally included the polar meteorological satellites and the geostationary meteorological satellites (GOES). Without certainty regarding the weather satellites' status, potential operators did not have a clear notion of what they were making proposals for. Baldrige's SEB was unable to jettison weather satellites entirely for several more months. Eventually, Congress had to intervene with legislation to resolve the weather and ocean satellite issue.

A second issue presented by the RFP to potential operators and the user community was its opaque details. For example, its November 1983 iteration had yet to identify which type of contract arrangement was most suitable for civil remote sensing. The government anticipated a cost plus fixed fee contract, which paid the operator a fixed fee while the government assumed research and development risks, but the RFP did not specify a fee or a time scale. Also, what remained unclear was the "the transition from Government to private ownership and operation [which] will involve some considerable period of time. The terms and conditions of an actual sale are expected to be part of a separate contract."[27] Essentially, the federal government reserved the right to set many contract details until after it had received interest from potential operators.

Another difficulty for potential operators was the national security provisions. This section of the November 1983 RFP was classified and not discussed in other sections. Unless the potential operator had staff with security clearances, it did not have a competitive edge to vie for the contract. Lastly, the RFP's "Commercialization Plan" section left many details to potential operators, a cause for great concern.[28]

As noted earlier, opposition emerged in the House, which voiced its frustration with civil remote sensing commercialization. While NOAA and the House agreed that weather and oceanic satellites should remain public assets, they disagreed on Landsat. By November, the House had put the weather satellite commercialization issue to rest. A 1984 authorization bill prohibited Baldrige from transferring civil land, weather, and ocean satellites to the private sector.[29] Weeks later, Representative Thomas Daschle (D-SD) announced that "by a vote of 377 to 28, the House went very strongly on record in opposition to any attempts to transfer this country's civil weather satellites and land natural resource satellites."[30] The vote passed House Concurrent Resolution 168, which became an expression of House opposition to commercialization, since

H. Con. Res. 168 did not have any binding legal authority over ending commercialization. The Senate indefinitely postponed its vote on the resolution. The House Committee on Government Operations also reported evidence of resistance to commercialization from Landsat's international cooperators. Furthermore, Daschle claimed on record that numerous committee and subcommittee chairs (controlled by Democrats in the 97th Congress) opposed land and weather satellite commercialization.

In late September 1983, J. Dexter Peach, Director of the GAO Resources, Community, and Economic Development Division, testified before the House Subcommittee on Legislation and National Security on international reactions to Landsat commercialization.[31] The GAO report surveyed several countries in Europe, Asia, and South America as well as the World Bank, Inter-American Development Bank, Asian Institute of Technology, and UN agencies such as the UN Environment Programme and UNESCO. These organizations argued that a commercial market had yet to be realized, but also disagreed with defining Landsat as an operational program. They told Peach that Landsat data "is used mostly on a research and development or demonstration basis rather than an operational basis." Furthermore, Landsat commercialization threatened "investments made by developing countries in acquiring the capability to receive and use Landsat data [which] represent significant commitments of their governments' resources."[32] Commercialization also deeply threatened international ground station operators' investment in Landsat, since the Memoranda of Understanding they had signed with the US government would terminate if Landsat ceased to operate.[33] Essentially, foreign operators and users saw commercialization as a termination of the nondiscriminatory data access policy. The foreign representatives argued that private operation of Landsat placed them "at an unfair economic disadvantage" and noted that "the satellites could be used to acquire and distribute military intelligence harmful to their national interests."[34] Without a guaranteed nondiscriminatory data access policy, foreign representatives feared for both their countries' economic development initiatives and their national sovereignty.

Congressional concerns and NOAA's continued RFP revisions began to shape civil remote sensing policy and the future of Landsat use. At the behest of both the House and NOAA, the SEB dismissed the possibility of weather and ocean remote sensing satellite commercialization by striking it from the RFP. NOAA kept Landsat on the table at the White

House's urging and despite House disapproval. Effectively the NOAA RFP attempted to set guidelines for a potential operator to foster commercial land imaging data use and define the segments of the satellite system ripe for private operation. However, the RFP continued to evolve into 1984 as Congressional reports and legislation kept Landsat in transition. Similar to GAO's reports, the Congressional Office of Technology Assessment published a report in 1984 that expressed concerns about data discontinuity and cost prohibition, and expressed further worries regarding Landsat commercialization.

Congress Votes for Commercialization: Land Remote Sensing Commercialization Act of 1984

Amid this tumult, two significant changes promised to expand data use as well as sustain the Landsat program for the next decade. On March 1, 1984, NASA launched Landsat 5, which became the longest operating of all Landsats to this day, capturing nearly 2.5 million images over 29 years, far outstripping its three year design life.[35] Landsat 5's longevity proved especially fortuitous given that President Reagan cut all proposed successors. Congress continued to debate new legislation that would ensure sustained funding, management, and new technologies that expanded data use. One week ahead of Landsat's 12th anniversary on July 17, 1984, President Reagan signed into law the Land Remote Sensing Commercialization Act of 1984 (Landsat Act). This legislation attempted to steer Landsat use toward commercialization; the new management regime struggled, however, and American land remote sensing nearly ended entirely.

When Reagan entered office in early 1981, he and OMB Director David Stockman set out to commercialize Landsat and weather satellites quickly, since they both were "philosophically opposed to any kind of 'operational' activity by the government. Once Landsat D [4] dies in 1985 and D' [5] in 1987 says the OMB, that will be the end."[36] Essentially, Reagan and OMB wanted the US government out of the remote sensing industry as soon as possible. As mentioned, NASA's role diminished, since it only built, launched, and maintained the satellites' orbits at this point. It played no role in data collection, distribution, analysis, or marketing. NOAA now managed Landsat on the launch of new satellites. In order to commercialize Landsat, an act of Congress was required, which Don Fuqua (D-FL) chairman of the House Committee on Science and Technology, introduced in the House of Representatives in 1984 as H.R. 4836. The bill, however, stated that Landsat and the weather satellites would be commercialized, which met with opposition.

The SEB began to study the weather satellite issue further and commercialization still required legislation from Congress. SEB's studies led its chairman, William Bishop, to oppose the commercialization of weather and ocean satellites, since "the only customer big enough to support them was the government."[37] In a response to OMB's request for Commerce's views on H.R. 4836, Bishop argued that the scope of the bill needed to narrow. He dispensed of ocean remote sensing from commercialization, stating that "there is no generally recognized operational capability in ocean remote sensing at the present time [1984]."[38]

Bishop continued to oppose the commercialization of ocean and weather satellites in his response to H.R. 4836 as SEB chairman. Congress and the SEB both opposed weather satellite commercialization, since weather data had become so important for public safety, namely in storm forecasting. Several members of Congress speculated that data companies could inflate data prices at a time of domestic emergency, which they argued was outside the national interest. As arguments against packaging Landsat with the weather satellites piled on, members of Congress began legislating against it. By fall 1983, both chambers of Congress had passed resolutions opposing the transfer of weather satellite operations to the private sector, a position which was solidified in November.

Congress passed an appropriations bill specifying that no funds would be allocated for NOAA "to transfer the ownership of any meteorological satellite or associated ground system to any private entity."[39] In addition, Fuqua recognized that commercializing weather satellites further impeded Landsat commercialization, and sponsored House Concurrent Resolution 168, which defined weather satellite data as a public good and prohibited weather satellite operation from commercialization. The resolution identified "the Federal Government as the principal user of data gathered by civil meteorological satellites" which is implemented in federally provided weather forecasts.[40] In Fuqua's support of the resolution on the House floor, he reiterated a joint NASA/DoD study's conclusion that "there is considerable financial, policy, and program risk to the Government in commercializing weather satellites and there is no clear policy or financial benefit to be realized."[41] The resolution overwhelmingly passed by 377 to 28. Subsequent legislation passed in March

1984 by Congress and signed by Reagan in July 1984 officially prohibited the commercialization of weather satellites, under the Land Remote Sensing Commercialization Act of 1984 (Landsat Act). Congress officially defined weather satellite data as a public good, but had yet to do so with Landsat data.

Accordingly, the SEB revised its request for proposals after Congress released its FY 1984 appropriations. It released a new request in January 1984 and received seven proposals from companies, including COMSAT, Fairchild Industries, Eastman Kodak, and an RCA/Hughes consortium. However, the SEB could not evaluate the proposals, since several included weather satellite operations, a policy as yet unresolved. Landsat commercialization would require legislation; the potential operators could not seize control of Landsat even if Commerce made an offer.

Even though Commerce solicited proposals and began the selection process, Baldrige needed legal authority to award a commercial contract for Landsat operations. In February 1984, the House introduced the bill that became the Landsat Act. The bill had several policy goals:

- Maintain American leadership in remote sensing, preserve national security, and meet foreign obligations
- Promote private sector involvement in remote sensing
- Minimize government subsidy (duration and amount)
- Open access data policy
- Prohibit meteorological satellite commercialization

The Landsat Act revealed several knowledge gaps between policymakers and lawmakers regarding Landsat use. As mentioned, the White House had pressured Commerce and Congress to commercialize weather and ocean satellites. Against numerous policy recommendations, however, Congress removed them from the bill altogether. Bishop remarked that "including ocean sensing within the scope of the bill will have the effect of specifying the Government's conditions for the commercialization of ocean remote sensing long before the parameters of such a system or the need for commercialization have been established," further stating that it may stifle innovation.[42]

Another gap between Commerce policymakers and the House bill involved data marketing, since no federal agency had such a task. The Landsat Act called for the Commerce Secretary to contract out data marketing services to a potential operator, which the SEB's RFP did not require. Thus, Bishop stated, "if the successful bidder in the RFP process does not market data, an additional procurement action would be required for the marketing component."[43] This gap between Commerce and the House, he added, complicated the commercialization process by requiring yet another contractual procurement, costing more time and dollars. Bishop encouraged Congress to include data marketing as a formal objective for the potential Landsat operating contractor to increase efficiency during the evaluation process.

The Landsat Act addressed concerns raised by both private industry and the scientific community. Fuqua recognized that slow market development meant that private industry and potential research outfits would not be able to plan long-term, multi-year studies without a guarantee of data continuity and a competitive market which could provide numerous data products. Ironically, the bill sought to maintain nondiscriminatory data access to broaden Landsat use, which private industry did not favor. Pamela Mack explained this irony, stating that "customers who would pay a high price for the exclusive use of Landsat data would not be interested if it were available to their competitors as well."[44] The Landsat Act essentially tried to reconcile the open access policy through fostering a remote sensing data market with a competitive industry.

The House revised and the Landsat Act cleared the House and Senate, making its way to Reagan's desk on July 17, 1984 as the Land Remote-Sensing Commercialization Act of 1984. At the bill's signing, Reagan reiterated his motivations for Landsat commercialization, asserting that the bill is "in the national interest," that it reduced "burdensome governmental regulation," and that it encouraged competition.[45] He also stated "we will make every effort to minimize the duration and amount of any Federal subsidy," a promise which plagued the very policy he promoted and the Landsat program itself over the next five years.[46]

Commercialization to Contract: NOAA takes Landsat to Market, 1984–1985

The Landsat Act provided the legal precedent necessary to offer Landsat officially to private-sector operators. Soon after its introduction, Commerce received 18 inquiries from firms interested in Landsat and weather satellite operations and data sales. However, the removal of weather satellites from commercialization prompted all but two potential operators to remove themselves from the competition. Between July 1984 and September 1985, Commerce essentially conducted a process of elimination to select the ultimate commercial operator for Landsat.

A consortium named Earth Observation Satellite Company (EOSAT) won the bid for Landsat operations. It divided the labor among three subcontractors. The Hughes Santa Barbara Research Center took responsibility for developing Landsat 6 and 7 instruments, which included a Thematic Mapper and Multispectral Linear Array Sensor, similar to the multispectral scanner. Meanwhile, RCA Astro-Electronics operated the "spacecraft bus and satellite operations control center" and Computer Sciences Corporation controlled "ground operations and ground receiving and processing facility design and Earthsat for market development and data enhancement."[47]

The US government completed the commercialization process with the September 27, 1985 signing of the contract between Commerce deputy Anthony Calio and EOSAT president Charles P. Williams. The contract obligated the federal government to operate the EROS Data Center, retain rights to the data, turn over operation of Landsats 4 and 5 (the only satellites in operation at that time), subsidize EOSAT up to $250 million paid out over five years, and subsidize Landsat 4 and 5 operations up to $20 million. The contract divided the $250 million among ground system development and Landsat 6 and 7 construction, launch, and integration. Lastly, the contract assumed that EOSAT would grow its revenue from $19 million in 1986 to $45 million in 1989.[48] In this way, EOSAT required fewer subsidies with each successive fiscal year. While the government and EOSAT clearly defined the division of labor and developed a collegial working relationship throughout the bidding process, the arrangement quickly fell into disarray when Commerce withheld portions of the $250 million promised to EOSAT. President Reagan's vow to reduce federal expenditures had begun to complicate the vision of commercialization that his Administration championed.

Commercialization Collapses, 1986–1989

Once EOSAT controlled the Landsat program and data marketing, it set about commercializing the satellite data. EOSAT's agreement with Congress stated that the Landsat Act included a $250 million subsidy for operational costs paid out over a 10 year transition period. Several months after the signing of the EOSAT contract, the federal government refused to "release the $69.5 million in government funds that EOSAT says it needs" during FY 1986 for new ground stations and for the development of additional satellites.[49] The dispute began between OMB and the House Science and Technology Committee. Legally, OMB could not release funds until Commerce approved the $27.5 million authorized by Congress for FY 1987, which fell short of EOSAT's needs. Reagan's proposed budget did not include funds for Landsat. Rep. Bill Nelson (D-FL) urged OMB director James Miller III to authorize Congressional funding, stating that "it would be a significant detriment to the country if this falls apart. We need remote sensing capability up in space for many reasons, not the least of which is national security." EOSAT president Charles Williams opined that the elimination of Landsat and its data would deleteriously "affect U.S. foreign relations, hand over technological leadership to the French, and destroy the first US. attempt to commercialize space."[50] At that time, the French had also developed a land remote sensing satellite, Systeme Probatoire de l'Observation de la Terre (SPOT), which launched in 1986 and began to compete with EOSAT for the remote sensing data market. Despite Williams' concerns, OMB director Miller opposed Landsat subsidies, arguing that the satellite costs ran too high. Both Rep. Nelson and Williams linked Landsat use to broad implications such as US foreign relations, since so many linkages had been put in place even prior to launch, and to technological leadership, a goal of American spaceflight endeavors both scientifically and commercially. EOSAT received its subsidy behind schedule for FY 1986, but the funding issues continued.

In January 1987, unpaid FY 1987 funds for EOSAT forced the company to terminate its efforts to build Landsats 6 and 7. As mentioned, EOSAT began receiving its $250 million subsidy, but "pressure from the Gramm-Rudman-Hollings deficit exercise led the White House OMB to delete the fiscal year 1987 installment of EOSAT's subsidy—$69.5 million."[51] In 1985, Congress passed the Gramm-Rudman-Hollings Balanced Budget Act, which required cuts in federal spending to reduce the federal budget deficit that had developed under the Reagan Administration. The Balanced Budget Act's policies filtered down to all federal agencies and their contracts, which made fulfilling the EOSAT subsidy far more difficult for NOAA, as federal expenditures remained high in the late 1980s. Congress restored only a fraction of what EOSAT was owed, about $27.5 million. Meanwhile, NOAA and EOSAT continued to negotiate its subsidy rate; despite the contractual obligation of $250 million and two new satellites, NOAA planned for $209 million and one new satellite. For EOSAT, the funding issue delayed construction of Landsat 6 and 700 employees faced potential layoff or reassignment.

In August 1987, the USGS feared EROS Data Center closure due to the federal budget shortfall extending from recent legislation and EOSAT's woes. EROS processed and distributed Landsat data prior to EOSAT's formation. It also lost about a third of its workload and revenue to EOSAT, in addition to about $7 million of its annual federal budget by 1989.[52]

Shrinking federal budgeting and inadequate private investment threatened not simply EROS, but the Landsat program itself in 1988 and into 1989. In 1988, the annual operational cost of Landsat totaled $18.8 million, but NOAA spokesman Bud Littin announced in early 1989, "we're out of money, that's all. The situation's pretty bleak."[53] In late 1988, NOAA ran short by $9.4 million for EOSAT subsidies. The news angered science advocate Rep. George Brown (D-CA), who stated "this is a damned outrage, and I'm going to do everything in my power to stop it from happening."[54] Brown, along with 103 other members of Congress, addressed a letter to President Bush and Vice President Dan Quayle "urging them to find a way to keep the Landsat remote sensing satellites in operation."[55] Quayle worked with Congress, but found few budgetary solutions. Landsat's situation was precarious: if Quayle and the National Space Council could not find funding for the satellites, NOAA threatened to "turn off Landsat 4 and 5 on March 27 [1989]."[56] Also, EOSAT speculated about the end of its data distribution services, effectively closing access to over 2 million Landsat images collected to date. It continued Landsat 6 development, since Congress had appropriated $36 million for construction, but not yet for launch.

The funding issue was the result of friction between Commerce's order to limit funds for Landsat and the satellite's advocates at NOAA, the Hill, and Dan Quayle of the National Space Council. NOAA's frustration grew with Commerce's obdurate funding attitude, one unnamed official lamenting "they [Commerce] don't give a damn about Landsat" and that "it is a very awkward situation—the user community should raise hell."[57] The DoD responded as a user of Landsat data. Quayle met with OMB director Richard Darman and proposed that DoD provide emergency funds to NOAA and EOSAT to resume Landsat operations for FY 1989, and eventually adopt Landsat 7 construction. Through

Quayle's discussions with DoD, NASA, and Congress, in September he secured funding for Landsat until the end of FY 1989. Beyond 1989, Landsat's fate rested on the Hill.

On September 6, 1989, the House began negotiations to provide emergency funds to EOSAT for Landsat under a bill designated for NOAA appropriations. The bill for Landsat funds, H.R. 2427, originated in the House Subcommittee on Natural Resources, Agricultural Research and Environment, and received bipartisan support. Rep. Bob Roe (D-NJ), chairman of the House Committee on Science, Space, and Technology, put forth H. Res. 230 and Rep. Jimmy Quillen (R-TN) spoke on its behalf. He acknowledged the funding crisis Landsat had been facing and the imminent threat to use, stating:

> the loss of these Landsat satellites would interrupt the availability of remote sensing data for key government, scientific and foreign users; abandon the substantial Federal investment ($1.5 billion) in a highly valuable data acquisition system; and severely damage, if not destroy, the Landsat commercialization initiative.[58]

Rep. Robert Walker (R-PA), chairman of the House Science Committee, continued to support Landsat, stating that the program "is absolutely critical to oil, gas, and mineral exploration, agricultural planning, global environmental monitoring."[59] More representatives rose in support of Landsat, mentioning uses in several states. In all, Quillen and Walker urged their fellow representatives to continue funding Landsat and secured a 380 to 1 vote in favor.

Reagan and Commerce's commitment to Landsat commercialization plunged the program into severe financial problems. Despite the introduction of new data from Landsat 4 and 5's Thematic Mapper and EOSAT's Landsat data archive, the company struggled to make a profit. Landsat advocates at NOAA, on the Hill, and the Vice President secured just enough funds for Landsat to live another fiscal year into 1990.

Commercial Consequences

By 1990, the commercialized Landsat system found itself in a precarious spot. EOSAT did not turn a profit off selling Landsat data, despite raising prices, nor were the satellites supported federally except for small subsidies meant to help EOSAT stand alone. In order to recover the costs of operation, NOAA and later EOSAT increased Landsat data prices throughout the 1980s. However, studies by Kathleen Eisenbeis and former EROS chief Donald Lauer and several colleagues demonstrated that Landsat data pricing and availability drove away users, especially in academic communities.[60] Landsat data came in two forms: film printouts of imagery and computer-compatible tapes (CCT). Lauer and his EROS colleagues depicted how average film and CCT prices increased steadily as sales dropped precipitously over the 10 years before and after commercialization.

Data sales held steady into 1981, but began to drop off in 1982 when both film and CCT prices went up to $20 and $250, respectively. From 1982 to 1984, the most serious plunge in data sales occurred when film prices tripled and CCT prices doubled. Sales recovered very modestly after the launch of Landsat 4 in 1984. The Landsat 4 platform included the Thematic Mapper, which was an upgrade of the multispectral scanner that flew aboard Landsats 1, 2, and 3. The Thematic Mapper had seven spectral bands, compared to the multispectral scanner's four and thus could gather more data. Data from the Thematic Mapper proved to be more problematic for the user, though, since EOSAT charged more for it and it often required higher processing power. Once EOSAT controlled Landsat data distribution in 1985, it sought to phase out film sales and focus on CCT sales. As mentioned, NOAA released its Landsat commercialization RFP in 1983, the same year film prices jumped $10 and CCTs doubled in price. EOSAT assumed full control of Landsat in 1986, when film item prices jumped from $60 to $125 (and accordingly 20,000 fewer images were sold) and CCTs doubled from $500 to $1,000. Film prices were hiked one more time in 1987 as the user base diminished further, signaled by another drop in sales. Figure 6.2, constructed with data collected from the US Geological Survey, depicts the aggregate sales of Landsat film and CCT products. Each product is one Landsat scene, which is a map of 180 square kilometers of the planet's surface.

Not only did the user community purchase less Landsat data, revenues did not meet the annual cost of Landsat system operations. Between 1979 and 1989, film revenue hovered around $2 million before dropping below $1 million in 1989. CCT revenue soared after commercialization to just over $9 million. Film revenue averaged $1,914,890 and CCTs averaged $4,181,127. Though revenues grew throughout the 1980s, EOSAT was unable to maintain cost recovery, per OMB

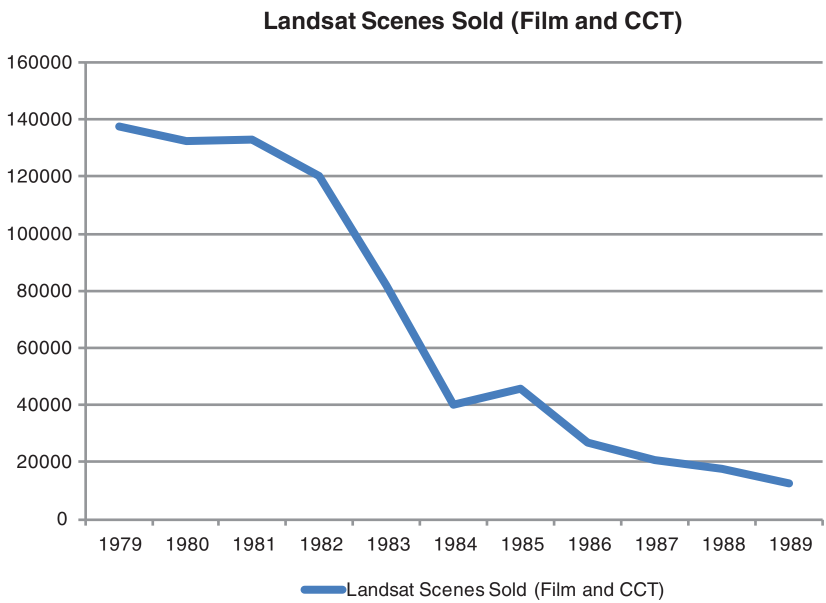

Fig. 6.2 Landsat scenes sold 1979–1989 (Data courtesy of US Geological Survey.)

requirements. It also drew in modest revenues from Landsat ground stations abroad. The agreements between EOSAT, previously struck by NASA, and international ground stations stipulated that EOSAT be paid an annual fee of $200,000 to receive Landsat data. Even at its peak revenue in 1986, at just above $10 million, EOSAT did not recover the nearly $18 million, mentioned above, that Landsat operations cost annually.

Another problem that affected Landsat data sales was international competition from the French SPOT system. The French remote sensing satellites, first launched in 1986, offered higher-resolution imagery at competitive prices. By 1988, SPOT equaled EOSAT's revenues and over the next two years outpaced EOSAT's stagnant revenues by roughly $3 million in 1989 and about $10 million in 1990. These efforts to recover costs through price hikes and federal subsidies provide several lessons from Landsat.

Lessons of Landsat

Landsat began as an experimental satellite program offering land remote sensing data to a broad range of potential users, fostered through numerous partnerships in order to build a community of users (Fig. 6.3). Once Landsat became an established program, both the Carter and Reagan Administrations encouraged commercialization. Reagan mobilized Congress, Department of Commerce, NOAA, and OMB to formulate policies that would facilitate Landsat's transition from an experimental program to a commercial entity. Commerce oversaw the transition, while

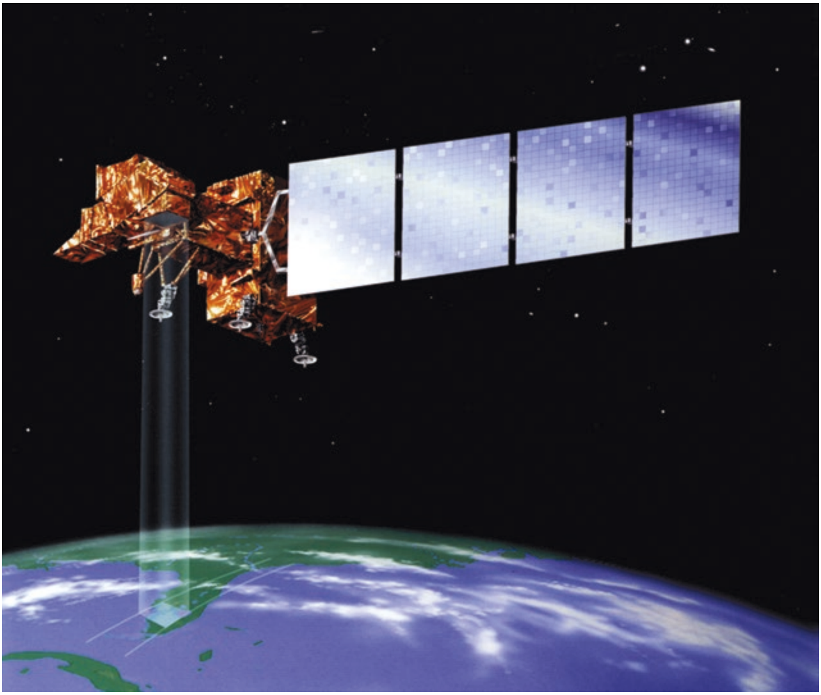

Fig. 6.3 Artist's conception of Landsat 7 satellite in orbit. This has provided repetitive acquisition of high-resolution multispectral data of the Earth's surface on a global basis since 1972. This data constitutes the longest record of the Earth's continental surfaces as seen from space (NASA, public domain. (Available at https://www.nasa.gov/offices/pae/ipao/home/ldcm_highlight.html))

NOAA wrote and rewrote numerous RFPs that increasingly marginalized industry from offering applications to operate Landsat. Congress passed major legislation that authorized the executive branch to commercialize Landsat. Meanwhile, OMB adopted a policy that required full cost recovery, which neither NOAA nor EOSAT ever achieved. Also, the Reagan Administration failed to supply EOSAT with the subsidies it was owed under contract in a timely manner. The result was data price hikes that drove away users. Reagan intended to reduce government regulation and expenditures to promote innovation in an emerging industry, but in effect, the combination of mandatory cost recovery, marginalizing RFPs, poor commitment to contractual obligations, and annual budget cuts unraveled the commercialization process and nearly ended the Landsat program entirely.

The first lesson from Landsat for understanding innovation concerns government-granted monopolies, in this case EOSAT, which attempted to deliver services and scientific data to a wide range of users, but ultimately failed to do so. As the Reagan Administration pushed the program from the public to the private sector meanwhile demanding cost recovery, both NOAA and EOSAT raised prices steadily throughout the 1980s. As a result, data sales dropped precipitously. Landsat's second lesson is that it demonstrates how innovation and commercialization lack linearity and can be a highly political process, as opposed to a product. Innovation, cast as commercialization, became a long political process, begun by a Carter Presidential Directive, and took the form of legislation and a contract between NOAA and EOSAT. The contract left little room for innovation, since it demanded that EOSAT recover costs, develop new Landsat satellites, and distribute data on a thin federal subsidy of $250 million. Landsat's third lesson is that innovation is different from commercialization, which can be observed in two ways. Landsat data was initially experimental, available at little cost to the user, and not meant for profitability, so it exhibits traits of a public good, such as nonrivalry and nonexcludability. Also, despite Landsat's broad range of applications, the market for land remote sensing data remained undeveloped. The Reagan Administration and OMB, among other commercialization proponents, often denied this reality, despite concerns expressed by members of Congress and NOAA. Over the course of Landsat's development from an experimental program to a commercial entity, its data became more difficult for users to acquire due to the very politics and policies meant to foster innovation.

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CHAPTER 7

Selling the Space Shuttle: Early Developments

John M. Logsdon

On January 5, 1972, President Richard Nixon met with NASA's top officials at the Western White House in San Clemente, CA, for the formal announcement of his approval of space shuttle development. In a statement issued after the meeting, the president said that the space shuttle would "revolutionize transportation into near space, by routinizing it," and that the shuttle would "take the astronomical costs out of astronautics." Because of these attributes, he added, "development of new space applications will be able to proceed much faster." In a "Space Shuttle Fact Sheet" issued at the same time as the President's statement, NASA indicated that "with the savings in launch costs, payload costs, and payload development time … the space shuttle will greatly increase the use of space by government agencies and commercial users, and lead to the discovery of new uses for space." Impressed by the shuttle's potential, *The New York Times* a few days later editorialized that "the space shuttle has the possibility of beginning for space travel what the Model T Ford did for the automobile age."[1]

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These very high expectations for innovations which would come from developing and operating the space shuttle provided the background within which NASA worked in bringing the vehicle into operation. Indeed, the shuttle itself was intended to be innovative; never before had there been a vehicle that could access space on a regular basis at much lower cost than previously possible. The shuttle's low cost and its regular operation, NASA anticipated, would encourage existing users of space, especially the developers, owners, and operators of communication satellites, rapidly to switch from the use of expendable launch vehicles to launching aboard the shuttle. In addition, NASA anticipated that by making it possible to carry research and development payloads into orbit at an affordable cost, providing an opportunity to operate those experiments in the high-vacuum, low-gravity space environment, and, if desired, return their results to Earth, the shuttle would lead to a wide range of discoveries. Those discoveries in turn would not only create significant social and economic benefits, but would also foster new demand for shuttle services.

Presidential approval of space shuttle development in January 1972 thus set NASA on two separate but ultimately converging paths. The first path, one with which NASA was comfortable, was the engineering task of developing a new space system. Even so, developing a partially reusable space transportation system that could provide regular access to space at a markedly lower cost than heretofore had been the case, while at the same time offering new capabilities for space operations, was a daunting challenge. The second path, one with which NASA had had only limited prior experience, was creating a policy framework for "selling the space shuttle." This framework would encourage all existing space operators—NASA, the Department of Defense (DoD), other US government agencies, foreign governments, and the commercial sector—to rely on the space shuttle as their means of access to space. That framework, NASA hoped, would also lead private-sector entities not previously involved in space activities—industrial firms, research laboratories, and universities—to experiment with innovative space uses.

This chapter describes how NASA during the 1972–1985 period responded to the challenges of pursuing the second of these paths, with a focus on shuttle use by US commercial entities and foreign organizations. It details the initial policies NASA put into place to encourage nongovernmental uses of the space shuttle's launch, in-orbit, and payload-return capabilities. It discusses the original pricing policy developed for such uses and the early revisions to that policy. It outlines the steps NASA took to identify and attract new nongovernmental users of the shuttle's capabilities. Finally, it summarizes NASA's approach to marketing the shuttle to commercial and foreign users, adopted when the shuttle entered operation in 1982, as the anticipated demand for the shuttle's services did not materialize and there was competition for it as a launcher for communications satellites.

It turned out that the high hopes for the shuttle as a means of routine and low-cost access to space were not realized: the space shuttle turned out to be an expensive and difficult-to-operate system, and by 1986 was banned by the White House from launching commercial payloads. Even so, between its first operational flight in November 1982 and the *Challenger* accident in January 1986, there were a number of commercial or commercially oriented space activities that it enabled. Among them were the launch of a number of commercial communications satellites, industrial development of new space hardware complementary to the shuttle, conduct of commercially oriented experiments in the microgravity environment, retrieval and reuse of satellites launched into an incorrect orbit, providing low-cost access to space for a number of university and industrial experimenters, and transporting into orbit a number of individuals not trained as astronauts. In addition, several of the policy innovations that NASA used to encourage nongovernment shuttle use have persisted to the current day.

Pricing the Space Shuttle

An early step in creating the framework for shuttle use by commercial and foreign entities was setting the price for such use. There were three categories of shuttle users for which NASA had to set a price: DoD, other US government civilian agencies, and commercial and foreign government users. NASA categorized US nongovernment users as "commercial," even if they might include nonprofit entities such as universities and research institutes. Only the pricing policy for the commercial category (including the launch of commercial or government-owned communication satellites from countries other than the USA) is discussed in this chapter.

NASA had been the world's sole provider, on a reimbursable basis, of launch services for commercial communications satellites since the mid-1960s. Pricing these services was relatively simple, involving totaling the one-time costs of an expendable launch vehicle (ELV) and of NASA's efforts in preparing that vehicle for the launch of a dedicated payload. By contrast, the shuttle could provide not only a launch service (even if only to near-Earth orbit), but also a number of other capabilities, including astronaut interaction with a payload, an upper stage to carry a payload to another orbit, particularly geostationary transfer orbit, extravehicular activity, and numerous other services. Each service beyond some basic level of a "standard mission" had to be priced. Also, it was unlikely that a commercial customer would occupy all of the large shuttle payload bay, 15 feet by 60 feet. That large volume had been chosen so that the shuttle could launch all potential government payloads, especially large photo-intelligence satellites and modules of a hoped-for space station. The shuttle was also being designed to be able to launch up to 65,000 pounds; there were no commercial payloads contemplated that would need such weight-lifting capability.[2] The most likely commercial missions for a shuttle would thus share payload bay space and not require all of the shuttle's lift capability. NASA had to take these factors into consideration in developing a shuttle pricing policy.

That policy, first articulated in early 1977, was based on the following principles:

- Since the space shuttle was to be a "national" system with its primary mission serving US government users, there would be no attempt to recoup a portion of the system's development costs in the price charged to nongovernmental and foreign users.
- While as a matter of national policy the goal over the shuttle's projected lifetime would be to recoup the actual costs of commercial shuttle launches, that goal would be met not by charging the actual cost of each commercial mission, but rather by charging the projected average cost of a launch over an initial 12-year period of operation. NASA recognized that in the early years of shuttle operation, launch costs would be high, both because NASA would still be learning how best to operate the shuttle most efficiently and because there would be fewer launches per year against which fixed operating costs could be charged. NASA thus decided that for the first three years of shuttle operations, the price of a shuttle mission, adjusted only for inflation, would be set at a less-than-cost level. Over the subsequent nine years, based on experience with actual shuttle operations, NASA would adjust upward the

> cost to commercial users, so that by the end of the 12-year period reimbursements from commercial users would match total costs of meeting their needs, making up for the "losses" in the first three years of operation. Keeping the initial shuttle price as low as possible was a way of encouraging existing commercial users to make an early transition from expendable launch vehicles to the shuttle, a high-priority NASA objective. *The New York Times* in January 1977 reported "'Bargain' Prices Set for Space Shuttle," and suggested that NASA officials "expect the reduced prices to attract more 'customers' … and to increase sharply orbital traffic in the 1980s."[3]

As the pricing policy was being developed, NASA was forecasting 572 operational shuttle launches over the 12-year period 1980–1991, with a launch rate varying from 3 operational launches in 1980 and 14 in 1981 to 65 launches in 1988. (No launches associated with developing a space station were included in this forecast.) The cost of those 572 launches, based on "a very thorough [and] detailed analysis of the total operations costs that we would encounter over a 12-year period," was projected to be $9.2 billion. (All costs are in FY 1975 dollars.) The average cost of a launch was thus $16.1 million. Given the uncertainties involved, NASA rounded up the average cost per launch to $18 million. To this $18 million estimate, for commercial users it added an obligatory $271 million charge for a payload reflight guarantee, in case the shuttle did not perform correctly, and a $4.3 million "user fee" to cover depreciation of NASA's shuttle facilities and equipment and amortization of the cost of producing a shuttle orbiter. This made the price for a dedicated commercial shuttle launch $22.6 million in FY 1975 dollars.[4]

NASA recognized that most commercial users of the shuttle (commercial payloads were estimated at 14% of the estimated 1091 payloads in the 560-mission model that NASA had adopted by spring 1977) would seldom, if ever, need a dedicated shuttle mission to accomplish their objectives. The space agency first defined a "full" shuttle mission as one using 75% of the shuttle's payload bay capacity, and then developed a formula based on the length or weight of the commercial payload, whichever was greater, and on the desired orbit to calculate what share of that 75% of the payload bay capacity and shuttle performance the payload required. That "load factor" determined the portion of the $22.6 million launch cost which would be charged to the user.

The $22.6 million base price covered only "standard shuttle services," including launch preparations, a three-person crew, one day of on-orbit operations, and payload deployment. Optional shuttle services, such as providing an upper stage to carry a payload to a nonshuttle orbit, meeting a particular launch window, conducting special crew training, revisiting or retrieving a payload, spending additional time on orbit, or carrying out extravehicular activity, would incur additional charges. For example, the charge for each extra day in orbit was $200,000–300,000; for an upper stage to carry a payload to a nonshuttle orbit, $75,000–85,000; for an extravehicular activity, $60,000–100,000; and for a mission to an initial altitude other than 160 nautical miles, $60,000–100,000.

NASA guaranteed the $22.6 million charge for a standard shuttle mission, adjusted only for inflation, for the first three years of shuttle operations. As noted above, this guaranteed launch price was not based on the projected actual cost of an early launch. Among other considerations, in order to attract existing commercial space operators to quickly transition to using the Shuttle, it was set to be substantially lower than the cost of launching an equivalent payload—in most cases, a communication satellite—on a Delta or Atlas-Centaur ELV. In 1977 NASA suggested that the launch of a Delta-class payload on the shuttle would be $8.67 million, compared to $14.2 million if a Delta were used; for a larger payload, the cost would be $16.3 million compared to $38.7 million if an Atlas-Centaur booster were employed. Demonstrating the cost savings from shuttle use and thus "encouraging" (in fact, subsidizing) the transition of commercial space firms from using ELVs to shuttle use was important to demonstrating the shuttle's value.

There were additional nuances in the pricing policy: additional charges for missions contracted less than the standard three years in advance of the planned launch date; penalties if a user canceled, postponed, or rescheduled a mission; and discounts if NASA was given the flexibility to launch a commercial payload on any shuttle flight in a particular year. As it set an initial pricing policy for the shuttle, NASA's role of operating a space transportation service for a wide variety of users was clearly not going to be a simple matter. Indeed, whether NASA should even continue to operate the shuttle once it was declared operational was already a controversial question; that issue will not be discussed here.[5] It is worth noting, however, that putting a government agency with its roots in research and development of advanced technology into the position of serving a wide variety of nongovernment users on a quasi-commercial operating basis was not an obviously appropriate or viable choice.

Revising the Initial Pricing Policy

The 1977 pricing policy was successful in attracting early commercial users to book launches of their communication satellites on the space shuttle. When the shuttle finally entered operational service in November 1982, the payloads on its initial mission included two commercial communication satellites. Over the 24 shuttle missions flown between November 1982 and January 1986, the period during which the original "bargain" shuttle price was in effect, 11 of those missions carried a total of 24 commercial communication satellites as part of their payloads (Fig. 7.1).[6]

It was not surprising that commercial users were willing to book flights aboard the space shuttle, since they were being offered prices significantly cheaper than they had been used to paying. Those prices turned out to be concessionary. That reality became the focus of strong criticism. Even before the first launch of the space shuttle in April 1981, the General Accounting Office (GAO) found that the estimated average cost of a shuttle launch had increased by 73%, from $18 million to $27.9 million in FY 1975 dollars. Half of the cost growth was the result of "design changes, added requirements, and inaccurate estimates. Other increases can be attributed to inaccurate inflation rates and a reduction of the mission model." By 1982, estimates were that flights during the first three years of shuttle operations, which NASA had committed to commercial customers at a share of $22.6 million a flight plus the cost of optional services, were likely to actually cost more than $60 million per flight. *Science* magazine described the situation as "budgetary hemorrhage," since "the contracts and agreements are signed, and for 3 years NASA is locked into the older prices."

NASA was forced to absorb in its budget, which was being reduced by the new Reagan Administration, the costs of each shuttle flight carrying commercial payloads above reimbursements from its customers. This would, observed GAO, in effect be a subsidy to the shuttle's non-NASA users at the expense of NASA's own scientific and application activities. (The gap between mission costs and user reimbursement was even greater for flights carrying DoD payloads. To maintain DoD support for the shuttle, NASA in 1977 had committed to an artificially low DoD

Fig. 7.1 Satellite Business Systems communication satellite being deployed from *Discovery* during the STS-41-D mission, August 30, 1984 (NASA, public domain. (Available at https://commons.wikimedia.org/wiki/File:STS41D-36-034.jpg))

launch price of $12.2 million per flight for the first six years of shuttle operations.) Among the alternatives recommended by GAO in February 1982 was that the NASA Administrator immediately void the 1977 shuttle pricing policy as it pertained to all shuttle users and "establish a price more in line with the cost to NASA to launch a Shuttle flight except for those launches that have legally binding agreements."[7]

NASA rejected this recommendation, refusing to revise its original pricing policy for the first three years of shuttle operations. To do so would have meant renegotiating existing contracts. With the requirement of a three-year lead time to contract for a launch, most if not all agreements with commercial shuttle users during the first three years of shuttle operations were already in place by 1982.

However, in mid-1982, with the experience of the first three shuttle test flights in hand, NASA did make significant changes in both shuttle expectations and future pricing. The mission model for the first 12 years of shuttle operations was cut to 312 flights; it had been 572 flights in 1976, 560 in 1977, and 487 in 1979. With fewer missions across which to spread shuttle costs, this made a price increase per mission unavoidable. With only the three test missions as a basis for estimating the actual costs of an operational shuttle mission, NASA proposed an interim pricing policy for the three years 1986–1988; during those years, it suggested, it would get a better sense of actual operating costs and set a full cost-recovery price for the future. Because of inflation, the $18.3 million price of a shuttle launch for foreign and commercial users in FY 1975 dollars (before the user fee) had risen to $38.3 million in FY 1982 dollars. In June 1982, NASA announced that the base price would increase by 85%, to $70.7 million in FY 1982 dollars. Even with this increase, it was not intending during the 1986–1988 interim period to recover the still uncertain full costs of each shuttle mission. Rather, the new price was intended to cover only the additive costs to NASA of flying a mission for a commercial user. With this action, it gave up its hope of recovering the total cost of non-NASA shuttle operations over the 12-year period 1982–1993, conceding that early shuttle flights would be "loss leaders."[8]

One reason for not attempting at this point to set a higher, full cost-recovery price for the shuttle was the unwelcome emergence of a competitor to it as a launcher for commercial communications satellites. Under the auspices of the European Space Agency, a new ELV, named Ariane, had been developed; its first launch was in December 1979. The Ariane design had been optimized for the role of launching communications satellites. In 1980, a consortium of European aerospace firms, banks, and the French space agency CNES (Ariane was primarily a French-motivated project) formed a company called Arianespace to oversee Ariane production and launching and to market the launcher on a worldwide basis. Arianespace set a goal of launching 30% of the world's commercial payloads; that objective set it in direct competition with the space shuttle for launch contracts. The first commercial customer for an Ariane launch was a US firm, GTE. The US response was, not surprisingly, chauvinistic: the notion of a European competitor to what had been a US monopoly in providing launch services was troubling to the White House and Congress, as well as to NASA. Threatened by Arianespace competition, the White House set the new shuttle price to be competitive with what Arianespace was offering and NASA initiated a global campaign to market shuttle launch services. That campaign will be described later in this chapter.

After setting the revised shuttle pricing policy for the 1986–1988 period in 1982, NASA then engaged in a contentious process within the US government to develop a shuttle pricing policy for 1989 and beyond that would balance the goals of cost recovery and international competitiveness. By this time, not only the Europeans but also the Soviet Union, China, and Japan had indicated their intent to enter the global launch market, and one US company was trying to commercialize the Delta ELV that the space shuttle had replaced. A July 30, 1985 decision by President Reagan set a new approach to shuttle pricing, saying that beginning in 1989 "Shuttle flight capacity will be sold at auction to foreign and commercial users," with the minimum acceptable bid for a dedicated shuttle flight in such an auction $74 million in FY 1982 dollars. This was a far cry from the pricing policy that NASA had articulated eight years earlier.[9]

The issue of what price to charge for the use of a space shuttle to launch a commercial payload became moot in the aftermath of the January 1986 *Challenger* accident. In August 1986, the White House announced that the shuttle would "no longer be in the business of launching private satellites."[10] This decision brought to a close the attempt that had been announced with such high hopes 14 years earlier: that the space shuttle would "revolutionize transportation into near space, by routinizing it," and that it would "take the astronomical costs out of astronautics." The shuttle would no longer serve as a "space truck," frequently hauling commercial and government payloads into orbit at a modest cost; that innovation in space transportation proved ultimately to be at best premature.[11]

Cultivating New Shuttle Users

The 1977 pricing policy and its successors were aimed primarily at convincing the manufacturers, owners, and operators of commercial communications satellites to launch their satellites aboard the space shuttle. However, NASA early on also recognized that if its promises with respect to the shuttle were to be made real, there was a need to attract new users to space activities and thus to create an increased demand for shuttle operations. As early as 1973, it created an STS (Space Transportation System, another name for the space shuttle) New User Development Program. A basic assumption of that program was that "a passive user development strategy, which assumes new users of the STS will come to NASA, will not be successful" and that "an active user development approach to stimulate the interest" of new users was required. NASA in 1973–1974 sponsored four studies "to develop techniques and methodologies for identifying new uses and new users in the educational, industrial, and international sectors."

Commenting on this effort, *Aviation Week & Space Technology* noted:

> NASA understands that a major problem in exploiting shuttle capabilities lies in a critical missing element—finding paying users for the system in sufficient numbers to use this new national resources economically … [B] ut there has been a notable lack of response from the non-aerospace industry, which could become the preponderant customer population of shuttle users.

NASA followed these initial studies by examining "what is required for a NASA user development activity and the tools/aids needed for the user development community." That examination concluded that for potential "new to space" users, who would not be familiar with the attributes of the space environment that could enhance their research efforts, "the benefits of space technology (crystal growth, biological processing, etc.) is the primary product to be marketed, with a correlation shown to using the STS as an economical mechanism for implementing an economically viable space operation." To demonstrate such a correlation, "hard data (flight demonstration) will be desirable."[12]

It is beyond the scope of this chapter to provide a full account of NASA's user development activities as they related to creating new customers for the services of the space shuttle. In addition to the activities described below, NASA from the early 1970s on directly funded research to be conducted on-board the shuttle and eventually a space station, and aimed at eventual commercial payoffs in areas such as materials processing in space. With the increased emphasis on space commercialization under the administration of President Reagan (1981–1989), NASA in 1984 created a Headquarters Office of Commercial Programs and became a partner with industry and academia in a number of Centers for the Commercial Development of Space.

It is worth remarking, however, that casting a government agency in the role of actively seeking to develop users for the services it provides was somewhat unusual; government agencies usually exist to serve the expressed needs and demands of citizens, not to create them. For a number of years in the 1970s and 1980s, NASA's commitment to making the space shuttle a means of opening up space to a wide variety of users and thus demonstrating its value to the nation overrode questions about the appropriate role of government in stimulating technological innovation.

Getaway Specials

An early programmatic response to the need for flight demonstrations of the benefits of working in the space environment took the form of NASA offering to fly at low cost "small, self-contained payloads" aboard the shuttle. Such payloads quickly became known as "getaway specials." NASA announced in January 1977 that on a space available basis it would fly in the shuttle payload bay "packages under 200 lb. (90.7 kg) and smaller than five cubic feet which require no Shuttle services (power, deployment, etc.) and are for R&D purposes." The price for flying a getaway special was to be negotiated based on size, weight, and the need for additional services from the shuttle or its crew, but the basic cost before additional services would range between $3000 and $10,000. NASA would make no judgment on the potential scientific merit of the proposed payload; it would ensure only that it was not intended for non-R&D purposes and posed no safety risk to the shuttle and its crew. An experimenter interested in taking advantage of flying a getaway special had only to pay NASA $500 in "earnest money" to begin discussions on such an opportunity.[13]

Within a few months of announcing the getaway special possibility, NASA had received $500 payments for 23 payloads, with "more coming." These payments came from individuals, universities, research institutes, and US and foreign companies. The director of Shuttle operations, Chet Lee, told Congress in 1977 that the getaway special program "has great potential, because it will get young people's creative thinking into space, and … will foster dedicated payloads later."[14] The first getaway special was flown on the fourth shuttle flight in June 1982; it comprised nine experiments developed by students at the University of Utah.

By August 1983, 16 getaway specials had flown on the shuttle, while earnest money for another 380 experiments had been paid to NASA. The last getaway special payload was flown in 2001; the program was terminated after the February 1, 2003 *Columbia* accident, as NASA focused subsequent shuttle flights on assembling the International Space Station.[15]

It is difficult to provide a summary judgment on the innovation payoffs from NASA's getaway special program. Certainly the opportunity to fly an experiment on the shuttle was an exciting opportunity for a large number of students, but there is little record of significant research payoffs from those and other getaway special experiments. At least in its early years, the effort "produced only modest returns." Of the first 16 getaway specials flown in 1982 and 1983, "about 40% … failed in important respects, and some produced no data at all." Nevertheless, "students learned from their experiences; even sophisticated professionals profited from their mistakes," while NASA "reaped a harvest of human interest stories." Over the 20-year lifetime of the getaway special program, 167 payloads were flown, including 67 from commercial and foreign experimenters, 59 from educational institutions, and 41 from US government agencies.[16]

There has, however, been a lasting impact of the getaway special program. The concept of providing low-cost access to space for university and other researchers has persisted in the form of NASA's facilitating those wanting to fly small "secondary payloads" to the International Space Station and on other missions.

Joint Endeavor Agreements

Even as it set an initial shuttle pricing policy in 1977, NASA recognized that there were likely to be "exceptional payloads" for which the policy would not apply. Such payloads would include "an experimental, new use of space" or "a first-time use of space that has great potential public value." In preparing for shuttle operations, it recognized that the 1958 Space Act, with its mandate to "contribute to the preservation of the role of the United States as a leader in aeronautical and space science and technology and their applications," had given the agency "other transactional authority" to enter into agreements through mechanisms other than those set out in the Federal Acquisition Regulations, thereby allowing it to enter into innovative research and development partnerships with the private sector. These "Space Act Agreements" included "engaging in joint arrangements with U.S. domestic concerns in research programs directed to … enhancement of U.S. commercial leadership utilizing the space environment."[17]

Among the instruments that NASA created to facilitate such arrangements was a Joint Endeavor Agreement (JEA). Under a JEA, a private participant and NASA would share common program objectives, program responsibilities, and financial risk. A JEA was "a legal agreement between equal partners … not a procurement; no funds are exchanged between NASA and the industrial partner." The industrial partner at its own expense would develop an experiment and the flight hardware to conduct it; as long as it met such basic criteria as "technical merit, contribution to innovation, and acceptable business arrangements," NASA would provide several free shuttle flights for the experiment. The industrial participant would retain "certain proprietary rights to the results, particularly the nonpatentable information that yields a competitive advantage."[18]

On January 25, 1980, NASA signed its first JEA, partnering with the aerospace firm McDonnell Douglas and an unnamed pharmaceutical firm (which turned out to be Ortho Pharmaceuticals, a subsidiary of Johnson & Johnson) "to determine the feasibility of separating biological materials in space using a process known as continuous-flow electrophoresis." The hope was to produce "substances useful in the diagnosis, treatment, or prevention of human or animal diseases.'[19] This opaque language was used because Ortho for competitive reasons wanted to keep secret the specific substance that was the target of its research.

This initial JEA was followed by an agreement between NASA and a San Diego firm, GTI Corporation, related to developing a space-based metallurgical furnace that others could use to investigate solidification in low gravity and another with a new Florida firm, Microgravity Research Associates (MRA), which was interested in growing large gallium-arsenide crystals in orbit. Unlike McDonnell Douglas and GTI, MRA was a new, entrepreneurial firm "conceived and organized for the sole purpose of engaging in the production and marketing of materials processed in space"; this was precisely the kind of new space user that NASA hoped to encourage through the JEA mechanism. The company's president was frank in admitting "that only through such a program [as the JEA], in which NASA accepts to share the front-end burden, could a small business organization … find an opportunity to enter into this very promising new frontier of materials processing in space."[20]

These initial JEAs were created in the context of high expectations of the commercial potential of space. In the early years of shuttle operations, as the Reagan Administration increased the emphasis on obtaining commercial returns from space projects and NASA sought approval for a space station as a platform for, among other purposes, commercial space activity, there were extremely bullish projections of the potential revenue from materials processing in space. One widely publicized estimate was that space-based manufacturing of drugs, materials to make semiconductors, and new types of glass would by the year 2000 reach over $40 billion.[21]

Based on such optimistic projections, one company, SPACEHAB, began in 1983 to seek private financing to develop a facility to fly aboard the space shuttle to provide additional space for microgravity experiments; another, Space Industries Incorporated, proposed to develop a free-flying Industrial Space Facility, to be serviced by the shuttle. The link between the shuttle and commercial activities in space seemed very robust.

The NASA–McDonnell Douglas partnership turned out to be the most fully realized of these early JEAs. Even before entering into the JEA, McDonnell Douglas had been interested in manufacturing equipment to be used for commercial purposes aboard the shuttle and ultimately a space station. The company had sought a partner from the pharmaceutical industry to investigate the practicality of employing in the microgravity environment of space a process called electrophoresis—using positive and negative electrical charges to separate molecules according to size—to produce small quantities of high-value pharmaceutical products. McDonnell Douglas was an early customer for a getaway special, but after the JEA option became available, the company decided to carry out a more ambitious experiment. It invested significant corporate resources in developing a device called the Continuous Flow Electrophoresis System (CFES) for flight aboard the shuttle. NASA had decided to make limited space available in lockers in the shuttle's crew compartment, designated "mid-deck" lockers, for experiments that would not fit into the containers for getaway specials (called GAS cans) and would require crew interaction to carry out, and the CFES, which weighed 250 kilograms, required such accommodation.

Under the JEA, NASA committed to seven flights of the CFES aboard the shuttle; those flights took place between 1982 and 1985. For those four flights, McDonnell Douglas trained one of the astronaut crew members to operate the CFES equipment, but on the final three flights, after a change in NASA policy to loosen the requirements for flying nonastronaut payload specialists to accompany experiments (discussed below), a McDonnell Douglas employee, Charles Walker, accompanied the CFES into orbit. He thus became the first commercially sponsored space flyer. While NASA was flying the CFES without charge as part of the JEA, McDonnell Douglas had to pay NASA $40,000 per flight for training Walker to fly into space to operate it and for his presence on the missions themselves.

Although there were some problems in getting the CFES to work properly, overall the results of the in-space experiments were promising, and by 1985 McDonnell Douglas was preparing a production-sized, automatically operated electrophoresis system to fly in the shuttle's payload bay. The company hoped to negotiate either an extension of the existing JEA or a new JEA with NASA for a few development flights of the new system before putting it into operation. However, also in 1985, Ortho, the pharmaceutical company working with McDonnell Douglas, withdrew its participation, deciding that there were less expensive, ground-based ways based on gene splicing to develop the product that had been the focus of its interest. This put McDonnell Douglas in the position of seeking other pharmaceutical companies, both US and foreign based, to partner with. Also by this time, NASA had gained White House approval to develop a space station, and using the station for space manufacturing activities was a long-term objective of the electrophoresis experiments.[22]

Then came the January 1986 *Challenger* accident and the change in national policy that mandated a low priority for commercial experimentation aboard the shuttle once it returned to flight. By 1988, McDonnell Douglas had decided that, after investing more than $20 million of the firm's resources, it would not continue with its "Electrophoresis in Space" project. Also, by this time the initial enthusiasm about the commercial potential of space manufacturing had considerably diminished. A 1988 review of "Industrial Applications of the Microgravity Environment" by the Space Applications Board of the National Research Council found that

> U.S. industry perceives little near-term incentive for manufacturing in space … representatives of pharmaceutical and electronic material corporations that participated in early experiments aimed directly at

> commercialization support the conclusion that early enthusiasm for commercial applications has given way to a more realistic assessment, and that there is little current interest in direct pursuit of applications.[23]

Faced with decisions such as those made by McDonnell Douglas and assessments such as those by the National Research Council, NASA had little choice but, as the space shuttle returned to flight in 1988, to de-emphasize its use to attract new commercial users to space, although shuttle-based, NASA-sponsored research aimed at eventual commercial applications would continue as preparing for the space station era began.

One lasting impact of the JEA experience was NASA's recognition that under the 1958 Space Act it had "other transaction authority." NASA has used this authority in recent years to enter into innovative partnerships with established and new space firms, in particular in developing the capability to transport cargo and eventually crew to the International Space Station on a commercial basis.

Marketing the Space Shuttle

As the space shuttle approached the beginning of its operational service in mid-1982, its role as the launcher of choice for carrying communications satellites into space was under challenge. As mentioned earlier, the European Ariane launcher was being aggressively promoted as an alternative to the shuttle for launching such satellites: Ariane's first commercial satellite launch contract, with the US firm GTE, was signed in November 1981, and Arianespace was striving to capture a significant share of the commercial launch market. As NASA adjusted the shuttle pricing policy in 1982, being price competitive with Ariane was an important consideration. In addition, the Soviet Union, China, and Japan were indicating their intent to enter the commercial launch market, and in the USA there was discussion of commercializing one or more of the expendable launch vehicles that the shuttle was intended to replace. These threats to the shuttle's role as the world's premier launch vehicle led NASA to propose a series of actions to market the shuttle actively to potential commercial and foreign users. In 1984, NASA's Office of Space Flight set out a shuttle "marketing plan" that noted that "Shuttle marketing activities have met with much success, but they are still in a developmental stage … The NASA marketing team needs to be stronger and more sophisticated in order to successfully compete with other marketing efforts."

The marketing plan identified the need for

> an aggressive promotional effort, tailored to the needs of the marketplace … emphasizing NASA's extensive experience and how the Shuttle can be used to help accomplish our customers' scientific and business objectives. Sales efforts will be directed toward those identified as potential STS customers to obtain launch commitments. This effort will take place through presentations and regular contact with individual customers as well as targeted audiences. Other government agencies who have influence with customers will also be targets of this activity. Promotional programs will also be directed towards others who influence customer decisions such as spacecraft manufacturers, trade associations, payload operators, and customers of payload products.[24]

Discussions of "sales teams," "potential customers," and "targeted audiences" were certainly departures from NASA's Apollo-era heritage. They reflected a NASA struggling both to fulfill the promises made when the space shuttle was approved and to adapt to a new Reagan Administration emphasis on commercializing space activities.

NASA used its astronauts as salespeople for attracting commercial users to the shuttle. The first operational launch of the space shuttle took place in November 1982; the primary payloads were two commercial communication satellites, ANIK-C3 and SBS-C. The two satellites were successfully deployed from the shuttle's payload bay, and the four-astronaut crew, who had advertised themselves as the "We Deliver" team, posed in the shuttle middeck holding a placard with that motto.

In addition to delivering communications satellites into an initial orbit, in 1984 the shuttle demonstrated a unique capability to retrieve them if circumstances demanded. Two communication satellites, the Indonesian Palapa-B2 and Western Union's Westar-VI, were successfully deployed from the shuttle payload bay during the February 1984 STS-11 mission, but on both satellites there was a failure of their transfer stages that left them stranded uselessly in low-Earth orbit. The satellites were insured, and the insurance companies paid compensation to both satellite owners, thereby becoming owners of the satellites. Then, during the November 1984 STS-19 mission, the insurance companies paid NASA to retrieve the satellites and return them to Earth for resale

Fig. 7.2 The crew of Shuttle mission STS-5 (clockwise from top, Robert Overmyer, Joe Allen, Vance Brand, Bill Lenoir) pose after on 12 November 1982 deploying the first two commercial communication satellites to be carried aloft by the space shuttle, ANIK C-3 and SBS-C. This was the Shuttle's first operational flight. (NASA photograph)

and relaunch. This retrieval mission was successful, and astronauts Dale Garner and Joe Allen proudly demonstrated a "For Sale" sign as they returned from the rescue spacewalks (Fig. 7.2).

The "We Deliver" motto also served as the title of a 12-page, colorfully illustrated and glossy 1983 brochure that NASA prepared to tout the shuttle's advantages. The document was printed in several languages, reflecting the worldwide character of NASA's marketing effort; one target audience were the attendees at the 1983 Paris Air Show. (NASA also brought the space shuttle test orbiter *Enterprise* to the Air Show as a featured attraction.) The brochure proclaimed that the space shuttle was "the most useful and versatile space transporter ever built. It has also demonstrated a remarkable suitability for delivering communication satellites to earth orbit." It claimed that "in all the world, you won't find the Shuttle's equal," that "you can't get a better price," and that "considering all cost factors associated with launching your satellite or other payload into space, you can't get a better price or more for your money than the Space Shuttle."[25] This marketing language was directly aimed at winning the competition with Ariane.

Offering a Ride into Space

As NASA in 1976 invited applications to join the astronaut corps for the space shuttle era, it recruited two categories of future space flyers. There would be pilot astronauts who would actually control the shuttle in various phases of its flights, and "mission specialist" astronauts who would operate the various experiments and carry out the other activities taking place during a shuttle mission. These were to be long-term positions: people selected would undergo two years of rigorous training before being certified as ready for flight. In addition, on research-intensive missions during which the shuttle would carry the large Spacelab pressurized laboratory in its payload bay, NASA indicated that there could be "payload specialists" to accompany experiments into orbit. These individuals would be expected to fly only once, would not be required to go through a rigorous NASA selection process, and would undergo a shorter training period than career astronauts. The use of payload specialists even for Spacelab missions was controversial. The leadership of the Johnson Space Center, in particular, eager to provide as many flight opportunities as possible for career astronauts, argued that all research activities aboard the shuttle could be carried out by mission specialists and that payload specialists would not add value to a particular mission.

In addition to those payload specialists operating Spacelab experiments, NASA's original policy allowed a customer purchasing more than 50% of a shuttle flight to nominate a payload specialist for that flight. No one took advantage of this opportunity. NASA Administrator James Beggs reviewed the policy in 1982 and found it "overly restrictive." In October 1982, in advance of the shuttle's first operational flight, NASA announced that "the minimum required payload factor" would be eliminated and that "flight opportunities for Payload Specialists will be made available on a reimbursable basis to all classes of Space Shuttle major payload customers, including foreign and domestic commercial customers." The new policy would go into effect for flights beginning in 1984.[26]

It was this change in policy that allowed McDonnell Douglas engineer Charles Walker to fly into space three times in 1984 and 1985 with the CFES experiment (Fig. 7.3). However, perhaps a more fundamental reason for the policy shift was the competition from Arianespace for commercial launch contracts. Arianespace enjoyed several advantages in

Fig. 7.3 Astronaut Dale Gardner holds up a "For Sale" sign after he and fellow astronaut Joe Allen, during the November 1984 STS-51-A mission, retrieved two communications satellites that had been stranded in a useless orbit after their February 1984 launch from the space shuttle. Allen's image is reflected in Gardner's spacesuit visor. (NASA, image number 51A-104-049, public domain. (Available at https://www.flickr.com/photos/nasacommons/7678545042/in/photolist-cGwxVC))

this competition. While NASA required commercial customers to pay the announced costs of their satellite launch in advance, Arianespace could offer flexible pricing and payment arrangements. Moreover, Arianespace could fly potential customers aboard the supersonic Concorde airliner to view an Ariane launch in French Guiana on the northern coast of South America. Allowing a space shuttle customer to select someone actually to go into orbit was a very attractive counter to the Arianespace marketing approach. As the policy shift was announced, the newsletter *Aerospace Daily* noted that "the opportunity to fly a specialist with the payloads provides a marketing attraction that Ariane will not be able to match."[27]

Before the use of the space shuttle to launch commercial satellites was ended after the *Challenger* accident, there were two occasions on which a non-US payload specialist flew into space with his country's satellite. In

June 1985, Sultan bin Salman bin Abdulaziz Al Saud, a member of the Saudi royal family, accompanied Arabsat-1B into orbit, and in November of that year, Mexican engineer Rudolfo Neri-Vela flew into space with the Morelos-B satellite. Walker, Al-Saud, and Neri-Vela were thus the only commercial payload specialists to complete space flight; a fourth such specialist, Hughes engineer Greg Jarvis, was aboard the January 1986 *Challenger* launch in which all seven of the crew died. (That mission, of course, also carried teacher-in-space Christa McAullife, who had been selected as the first citizen-in-space to demonstrate that the shuttle was safe enough to carry ordinary individuals; a journalist was to follow later in 1986.) As part of the post-*Challenger* policy changes, the notion of the shuttle carrying commercial payload specialists and other nonastronaut "spaceflight participants" was abandoned.

In addition, a more political form of shuttle marketing took into orbit two US politicians critical to NASA's Congressional support. Senator Jake Garn (R-UT) flew aboard a mission in April 1985 and Representative Bill Nelson (D-FL) was aboard the January 1986 flight that preceded the *Challenger* launch.

A Private-Sector Alternative?

In February 1982, *The New York Times* reported that "a private company is seeking to buy a space shuttle." The Space Transportation Company (SpaceTran) of Princeton, NJ proposed to finance the construction of a shuttle orbiter and provide it to NASA for integration into NASA's shuttle fleet. In return, the company would take over from NASA the marketing of shuttle services to commercial and foreign users. SpaceTran was headed by economist Klaus Heiss, whose optimistic analyses of shuttle economics had in 1971 been a factor in the Nixon Administration's decision to approve shuttle development.[28]

As an initial step in gaining support for its initiative, SpaceTran hired a Washington lawyer with good connections to the Reagan White House. That individual, Joseph Blatchford, wrote White House Chief of Staff Edwin Meese soon after SpaceTran's proposal had been submitted to NASA, saying that the proposal could be "a major plank in the President's space program," and that "private enterprise would take over the function of marketing the U.S. space program to all domestic commercial and foreign users." He suggested that "an aggressive private marketing effort of our Space Shuttle program will compete successfully with the private

European aerospace program." Later in 1982, Heiss wrote Reagan's national security advisor William Clark, noting that "Europe has already chosen a private commercial approach" (Arianespace) to marketing space transportation capabilities, and that if the SpaceTran or a similar approach were not pursued, the result would be leaving "the United States … as the lone country mired in a multiple government agency approach to developing the commercial space business." Heiss suggested that SpaceTran's approach could "do that which the government … cannot do effectively, i.e., market the National Space Transportation System in worldwide competition" and "enable the United States to capture its 'share' of the next decade's potential space market," matching "vigorous efforts by the Europeans, the Soviets, and, in the near future, the Japanese."[29]

The SpaceTran proposal was ultimately not accepted by NASA. In addition, in 1984 Astrotech, a company headed by Willard Rockwell, the retired head of Rockwell International, the company that built the Space Shuttle orbiter, also proposed to finance a fifth shuttle orbiter. In return, Astrotech would lease a portion of the overall shuttle fleet capacity and market that capacity on a commercial basis. That proposal also was not pursued. While NASA in the mid-1980s was already considering transferring control over shuttle operations to a private-sector entity by the end of the decade, there was no perceived need for a fifth shuttle orbiter, and thus no business case for the deal offered by first SpaceTran and then Astrotech.[30]

In the aftermath of the *Challenger* accident and the consequent Reagan Administration decision to end the use of the space shuttle to launch commercial payloads, the need for a shuttle marketing effort disappeared. "Selling the space shuttle" to commercial users, never a comfortable NASA role, would no longer be necessary.

Lessons Learned

From an overall US interest perspective, there were good reasons for promoting the widest possible shuttle use, even if it was an awkward role for NASA to fill. They were well articulated in a 1984 memorandum from Reagan's then national security advisor Robert "Bud" McFarlane in the context of the ongoing interagency debate over what price to charge for shuttle missions beginning in FY 1988:

- "We have evidence to suggest that the French Ariane ELV would be the primary beneficiary of an increase in Shuttle prices." McFarlane suggested that if the price of a shuttle mission were increased, Ariane would capture an "even larger share of the market" and that such a result "would obviously undercut the President's primary goal of maintaining space leadership." This was because "the Space Shuttle is an effective means for promoting international cooperation, good will and technological growth among our friends and allies … The flight of foreign astronauts on the Shuttle along with their payloads is one example of how the President uses the Shuttle toward these ends."

- "Diminishing the Shuttle's competitiveness could also be counterproductive to our … space commercialization goals. NASA is attempting to encourage commercial users to capitalize on the unique attributes offered by the manned capabilities of the Shuttle." It was important that "the potential of the Shuttle to spawn new industries … should not be discouraged."
- "A reduction in foreign and domestic launches … could possibly result in increased prices charged for U.S. government launches … A reduction in Shuttle subsidies to foreign and commercial users could conceivably be offset by increased prices to government users."[31]

However persuasive the rationale for "selling the shuttle," the marketing effort ultimately floundered because it was based on an illusory foundation. By 1984 it was apparent that the system was not going to "take the astronomical costs out of astronautics" nor "revolutionize transportation into near space by routinizing it," to cite the claims made by President Nixon as he announced approval of shuttle development on January 5, 1972. Those developing the initial framework for shuttle use, including shuttle pricing policy, as late as the 1977–1980 period based their decisions on projections of both an unrealistically high flight rate and unrealistically low cost for shuttle operations. The inertia associated with that initial framework proved difficult to overcome in the early years of shuttle operations; it took the cruel shock of the *Challenger* accident to convince NASA, the White House, and Congress that seeking to launch the shuttle as often as possible was not a desirable course of action. Even at the time of the accident, NASA was planning to build up the shuttle launch rate to 24 missions per year, after launching 9 missions in 1985. As it turned out, over its 30-year, 135-flight lifetime, the shuttle was launched an average of 4.3 times per year.

Engineering Realities

A fundamental lesson from the experience of encouraging frequent use of the space shuttle by commercial and foreign customers, and then undertaking user development and marketing activities to promote such use, is that engineering realities cannot be ignored. The space shuttle system that NASA developed during the 1970s was a technological marvel, but it quickly proved incapable of meeting the premises regarding its cost and operability upon which NASA was basing its plans. NASA and its political and industrial supporters were heavily invested in these premises, and the space agency moved forward in the early years of shuttle operations as if they remained valid, while actual experience demonstrated that they were not achievable. This disjoint between expectations and reality proved very difficult to bridge, persisting even after the shuttle returned to flight in 1988 following the *Challenger* accident. Writing after a second fatal shuttle accident in 2003, the Columbia Accident Investigation Board noted that "throughout the history of the [Shuttle] program, a gap has persisted between the rhetoric NASA has used to market the Space Shuttle and operational reality, leading to an enduring image of the Shuttle as capable of safely and routinely carrying out missions with little risk."[32]

It is almost facile to suggest that in proposing the shuttle for development in the 1969–1972 period, NASA should have been more realistic in projecting the system's capabilities. Yet NASA was in the midst of six successful human missions to the Moon, and had justifiable pride in its engineering capabilities. There was significant opposition to shuttle approval within the White House technical and budget staff, and NASA was forced into justifying the shuttle as "cost effective" to moderate that criticism. President Nixon and his political advisors were interested in using the shuttle to continue human space flight and thereby project an image of US space leadership; in addition, they saw shuttle approval as a political gambit, creating jobs in key electoral states in advance of Nixon's 1972 reelection campaign. They thus discounted the technical and economic criticisms of the presidential staff. Once the shuttle gained initial White House and Congressional support, it traversed a risky political path to its initial flight; in particular, the Carter Administration in the late 1970s gave serious consideration to canceling the program. There were thus strong incentives for NASA continuing to move forward as if the shuttle's initial promises remained valid; to admit that they were unlikely to be achieved was a threat to program survival.

It is impossible in retrospect to make a judgment with respect to whether those in NASA and industry in charge of the shuttle program in its early years recognized that the vehicle would fall short of being able to achieve its cost and operability goals, or whether they were engaged in a form of mutual self-delusion, making plans as if those goals were realistic. Whichever the case, by the time the shuttle began flying, its failure to meet expectations was preordained.

Could this situation have been avoided? Perhaps. As he considered whether to approve shuttle development in late 1971, Nixon was presented with two alternatives. One was the large shuttle that NASA was advocating; the other, advocated by his budget and technical staff, was a more modest project to demonstrate the technologies required for frequent, lower-cost operations of a reusable space transportation system. Developing such an interim vehicle during the 1970s would have avoided the overly optimistic projections of shuttle performance. For the reasons discussed above, Nixon chose the NASA alternative. This was a flawed choice with long-lasting consequences.[33]

Economic Payoffs

The unrealistic optimism with respect to shuttle performance was paralleled by perhaps even more unrealistically exuberant projections of the economic payoffs of the activities—particularly materials processing in space—that the shuttle would help enable. Once again, these projections had little scientific basis and did not reflect the specific difficulties of operating in the unforgiving space environment. NASA actively encouraged potential new space users to investigate various approaches to commercially oriented research aboard the shuttle, and accompanied that encouragement with subsidized prices and almost an evangelical approach to shuttle marketing. This effort too had elements of mutual self-delusion. Neither NASA nor those in the private sector who hoped to benefit from shuttle-based research had any interest in fostering a realistic assessment of potential research payoffs leading to commercial returns. Such an assessment could have undercut their plans for shuttle use. Their optimism was reinforced by a Reagan White House eager to advance the commercial uses of space.

In summary, then, the various dimensions of "selling the space shuttle" represent a failure of the space community both within and outside of government to base plans for using the shuttle on an honest assessment of the system's potential. The seeds of this failure were sown when NASA from 1969–1972 sought approval for shuttle development as its major post-Apollo project. They germinated during the 1970s as NASA promoted shuttle use by existing and new customers. Nevertheless, as the shuttle entered operations, it soon became clear that those seeds were not going to result in healthy growth. As former NASA Administrator Mike Griffin commented as the space shuttle approached retirement in 2011, "what the shuttle does is stunning, but it is stunningly less than what was predicted."[34]

Policy and Program Innovations

In addition to these cautionary lessons drawn from the experience of marketing the space shuttle, there were several policy and program innovations associated with the marketing effort that have had a lasting positive impact. One was the first use of NASA's "other transaction authority" provided by the 1958 Space Act. Another was finding ways, such as the getaway special program, to facilitate low-cost access to the orbital space environment for researchers not ready or able to commit the resources required for full-scale space-based experiments. In crafting JEAs with companies eager to explore the potential of working in space, NASA discovered in its other transactional authority a flexible instrument that allowed it to work with the private sector outside of the strictures of the Federal Acquisition Regulations. Its experience with JEAs set the stage for NASA's use two decades and more later of Space Act Agreements to facilitate public/private partnerships in space activity. Similarly, NASA's experience with its getaway special program set the precedent during the space station era of its creating opportunities for low-cost experimentation aboard the International Space Station.

Notes

1. The presidential statement and Space Shuttle Fact Sheet were attached to NASA Press Release 72–05, January 5, 1972. A copy of the press release is in Folder 594 in the NASA Historical Reference Collection, NASA Headquarters, Washington, DC. (NHRC). "Investment in the Future," *The New York Times*, January 8, 1972, 28.

2. For a discussion of the factors leading to the size of the Shuttle payload bay, see Chap. 9 in John M. Logsdon, *After Apollo? Richard Nixon and the American Space Program* (New York: Palgrave Macmillan, 2015).
3. John Noble Wilford, "'Bargain' Prices Set for the Space Shuttle," *New York Times*, January 13, 1977, 21.
4. Information regarding shuttle pricing policy in this and subsequent paragraphs is drawn from House Committee on Science and Technology, "Hearings – Space Transportation System," May 17–18, 1977 and NASA, *Space Transportation Reimbursement Guide*, JSC–11802, May 1980.
5. For an early discussion of whether NASA or some other entity should manage shuttle operations, see General Accounting Office, *Issues Concerning the Future Operation of the Space Transportation System*, MASAD-83-6, December 28, 1982.
6. Craig Couvalt, "Shuttle Payloads Filled to August, 1981," *Aviation Week& Space Technology*, August 1, 1977, 58–59. Memorandum from Chester Lee to Johnson Space Center and Kennedy Space Center, "Flight Assignment Baseline Documents," November 5, 1979, Folder 1276, NHRC. For accounts of early shuttle flights, see Dennis R. Jenkins, *Space Shuttle: The History of the National Space Transportation System* (Stillwater, MN: Voyageur Press, 2002) and David M. Harland, *The Story of the Space Shuttle* (Chichester, UK: Praxis Publishing, 2004).
7. General Accounting Office, *NASA Must Reconsider Operations Pricing to Compensate for Cost Growth on the Space Transportation System*, Report MASAD-82–15, February 23, 1982. The quoted recommendation is on p. iii. Mitchell Waldrop, "NASA Struggles with Space Shuttle Pricing," *Science*, April 16, 1982, 278–279.
8. Mitchell Waldrop, "NASA Cuts Flights, Sets New Shuttle Price," *Science*, July 2, 1982, 35.
9. White House, National Security Decision Directive 181, "Shuttle Pricing for Foreign and Commercial Users," July 30, 1985. See Congressional Budget Office, *Pricing Options for the Space Shuttle*, March 1985 for an overview of the issues in this debate.
10. President Ronald Reagan, "Statement by the President," August 15, 1986, reprinted in John M. Logsdon et al., eds, *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program*, Volume IV, Accessing Space, NASA SP-4407 (Washington, DC: Government Printing Office, 1999).
11. Commenting on a draft of this chapter, Roger Launius suggested that the space shuttle did indeed achieve its goal of routine access to space. He based this conclusion on the observation that the process of readying a shuttle for launch had become regularized and thus "routine." My use of the term "routine" in this chapter has a different connotation; by

"routine" I mean, as I think was the intent at the inception of the shuttle program, shuttle flights on a regular and frequent basis. While at the start of the shuttle program the anticipation was 40 or more launches per year, the average launch rate over the 30 years of shuttle operations was 4.3 launches per year.

12. Batelle Columbus Laboratories, "Final Report on Phase II New User Development Program," Volume I, Executive Summary, March 26, 1976, 1, 2, 4. Erwin Bulban, "Non-Aerospace Firms Eyed for Shuttle," *Aviation Week & Space Technology*, April 4, 1976, quoted in Joan Lisa Bromberg, *NASA and the Space Industry* (Baltimore, MD: The Johns Hopkins University Press, 1999), 104.
13. Chester M. Lee, "The NASA Small Self-Contained Payload Programme," *Spaceflight*, May 1979, 197–202.
14. House Committee on Science and Technology, "Hearings," 157.
15. Ibid, 156–157; Philip Boffey, "Getaway Specials Seen as Less Than a Great Success," *The New York Times*, October 11, 1983.
16. Boffey, October 11, 1983. I am grateful to Gerry Daelemans at NASA's Goddard Space Flight Center for providing background information on the Getaway Specials program.
17. *Space Transportation Reimbursement Guide, 1–9;* House Committee on Science and Technology, "Hearings—The Space Industrialization Act of 1979," May 23, 1979, 72.
18. Office of Technology Assessment, U.S. Congress, *Civilian Space Policy and Applications*, 1982, 229.
19. NASA News Release 80–12, "Joint Endeavor to Stimulate the Commercialization of Space," January 25, 1980.
20. Richard Randolph, "NASA Industry Joint Venture on a Commercial Materials Processing in Space Idea," 1982, commons.erau.edu/cgi/viewcontent.cgi?article=2497&context=space
21. This projection is cited in Space Applications Board, National Research Council, *Industrial Applications of the Microgravity Environment* (Washington, DC: National Academies Press, 1988), 26.
22. The primary source for the account in the following paragraphs is a NASA Johnson Space Center Oral History Interview with Charles Walker, November 7, 2006, available at http://www.jsc.nasa.gov/history/oral_histories/WalkerCD/WalkerCD_11-7-06.pdf. See also Harland, *The Story of the Space Shuttle*, 212–216.
23. Space Applications Board, *Industrial Applications*, 31.
24. Office of Space Flight, NASA, "The Space Transportation Marketing Plan," June 1984, 5–6.
25. The text of the brochure is reprinted in Logsdon et al., eds., *Exploring the Unknown*, Volume IV, Accessing Space, 423–426.

26. Letter from James Beggs to Representative Don Fuqua, October 7, 1982; NASA Press Release, "NASA Expands Payload Specialist Opportunities," October 22, 1982, both in Folder 8960, NHRC.
27. "Shuttle Customers will be Allowed to Fly Specialist with Payload," *Aerospace Daily*, October 1, 1982, Folder 8960, NHRC.
28. "Private Concern Seeks to Buy a Space Shuttle," *The New York Times*, February 10, 1982.
29. Letter from Joseph H. Blatchford to Edwin Meese III, February 10, 1982, Folder 12772, NHRC. Letter from Klaus Heiss to William Clark, December 17, 1982. I am grateful to Valerie Neal of the Smithsonian National Air and Space Museum for providing a copy of this letter.
30. Hugh Vickery, "Private Sector Presses Plans for Space Shuttle Operations," *The Washington Times*, November 23, 1984, 6C.
31. Memorandum from Robert C. McFarlane to Elizabeth Dole, "STS Pricing Issue," June 21, 1984, Folder 12772, NHRC.
32. Columbia Accident Investigation Board, *Report*, August 2003, 23.
33. This analysis is based on Logsdon, *After Apollo?* 295–299.
34. Michael D. Griffin, "The Legacy of the Space Shuttle" in Wayne Hale, ed., *Wings in Orbit: Scientific and Engineering Legacies of the Space Shuttle, 1971–2010*, 514. The book is available at http://www.nasa.gov/centers/johnson/wingsinorbit/.

CHAPTER 8

Something Borrowed, Something Blue: Repurposing NASA's Spacecraft

Matthew H. Hersch

In his 1996 study of the invention of the airplane, *The Dream and the Power*, French historian Emmanuel Chadeau describes the culture of early aviation enthusiasts as one of *bricolage*—a form of inspired recycling and tinkering that challenged creative, but resource-limited engineers to imagine new uses for existing materials and machines.[1] Early American aviators like Octave Chanute, Orville and Wilbur Wright, and Glenn Curtis did not attempt to fabricate airplanes from raw materials. Rather, they brought to the problem of flight both rigorous analytical methods and the ability to combine the methods, tools, and components of a variety of craft practices—from bicycle wheels to curtain rods—to build their flying machines. These were the inventors who enjoyed the most success; competitors like Frenchman Clément Ader, by contrast, toiled over machines of unwieldy novelty. Ader in particular, Chadeau writes, insisted on fabricating all of his machine's components from "boiler pipes to the smallest bolt," bankrupting himself and producing "an apparatus of disarming and costly complexity."[2]

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While much of the study of invention and innovation in space exploration focuses on the creation of new technologies, some of NASA's most ambitious efforts and important technical and budgetary successes have surrounded efforts to modify existing spacecraft to serve new functions. As NASA prepared its costly, technically challenging, and innovative Space Transportation System for flight in the 1970s, it simultaneously demonstrated that surplus Project Apollo hardware intended to fly to the Moon could be successfully reengineered to accomplish other worthy spaceflight goals, more quickly and more cheaply than could other proposed architectures. Examples of creative reuse include technologies associated with the Apollo–Soyuz Test Project and the Skylab space station (which drew heavily from the 1960s' Project Apollo and Project Gemini, as well as ambitious efforts to extend Skylab's life into the space shuttle era of the 1980 s. Rather than being a footnote to the history of NASA innovation, these efforts reflected a remarkable degree of engineering flexibility and inventive skill within the agency, and continued a longstanding tradition of *bricolage* in aviation innovation.

Bricolage in NASA Spaceflight Programs

Aerospace innovators have rarely had the luxury of unlimited funds or time to build their flying machines. Even during the relatively flush Cold War, when Congress appropriated billions of dollars to projects connected to national security, engineers worked within budgetary limits and schedules that prevented them from fabricating new technologies to fulfill all of their design needs. Had American scientific and military personnel enjoyed lavish funding to support spaceflight research in the late 1940s, they might have pursued a variety of exotic vehicles, including single-stage-to-orbit craft that would push the limits of even current technology.[3] Instead, the urgency of superpower competition and competing budgetary priorities required that the USA repurpose a variety of existing launch vehicles, upper stages, and spacecraft to ensure timely completion of national space policy goals.

The first American artificial Earth satellite blasted into orbit atop a vehicle cobbled together from military rocket programs, including the Redstone missile and clustered solid rocket motors from the MGM-29 Sergeant. A later variant of the Redstone launched the first American astronaut into space, and over the next half-decade, other Army, Navy, and Air Force missiles like Atlas, Titan, and Thor, sometimes combined with an upper stage developed for reconnaissance satellites (Agena) or interplanetary flight (Centaur), launched the bulk of NASA's manned and unmanned space vehicles. The Saturn I/IB family of vehicles, built under the supervision of Wernher von Braun at the Marshall Space Flight Center (MSFC) in Huntsville, AL (who had supervised the Redstone design as well), combined clustered engines and tankage from the Jupiter, Redstone, and Thor programs, as well as a variety of technologies influenced by older vehicles.

Spacecraft, too, often saw their capabilities enhanced and extended. An enlargement of the single-seat Project Mercury spacecraft produced the highly successful two-seat Project Gemini vehicle. Though ultimately not pursued, Gemini was the basis for design studies and short-lived experimental programs turning the craft into large-crew shuttle vehicle, a space station (the USAF Manned Orbiting Laboratory), and a circumlunar exploration craft, achievable by mating the craft with additional repurposed rocket hardware.[4] While Gemini never flew to the Moon, it did achieve a manned altitude record by rendezvousing with an Agena upper stage launched separately into Earth orbit.[5] While not without cost, these programs would have realized important exploration objectives with budgets much smaller than that of Apollo: each obviated the need to build new vehicles to perform functions demanded by national space policy leaders.

Historians of technology often use the term "path dependence" to describe the constraints on choice created by the prior adoption of particular technical infrastructures. While this phrase is often used pejoratively, path dependence presents both a challenge and an opportunity. As spaceflight appropriations declined in the late 1960s, enlightened reuse of Apollo components increasingly emerged as the only technique available to finance diverse human spaceflight activities. Throughout the 1960s, this effort always constituted something of a "pet" project for NASA engineers, and was often starved of funds and status within the agency. The program went through a succession of name changes, ending, ultimately, with the Apollo Applications Program (AAP), which only hinted at the significance of the engineering challenges it would undertake. Commitments by NASA to develop the space shuttle after 1972 threatened to swallow both AAP and NASA's entire human exploration budget; if not for clever efforts to recycle and repurpose existing equipment, NASA would not have achieved a number of program successes of the 1970s, including the launch and exploitation of the Skylab Orbital

Workshop (OWS) in 1973. Throughout the decade that followed, NASA attempted to capitalize its investment, both in operating and maintaining the workshop as an early space station and in examining efforts to extend its life into the space shuttle era.

Building Skylab

In 1973 and 1974, three crews of American astronauts visited an orbiting space station that had been launched intact on a single flight and possessed so much internal volume that astronauts could test prototype jetpacks within the pressurized crew compartment. For Skylab, the critical element in achieving cost efficiencies was a design goal, present from the earliest studies by contractors and engineers at MSFC, NASA's Manned Spacecraft Center (MSC) in Houston, TX, and NASA's Langley Research Center in Virginia, to make use of every pound of mass that American rockets launched into orbit, including discarded rocket stages, which were usually allowed to decay naturally and reenter Earth's atmosphere, burning up and fragmenting over the ocean. Instead, engineers at various US Army, NASA, and contractor facilities realized almost simultaneously that the often large, empty fuel tanks of these stages could be vented of remaining propellant by spacesuited astronauts, resealed, and pressurized with breathable air to create orbiting habitats at little or no cost. Skylab emerged as such a proposal: to vent the remaining fuel from an expended Apollo–Saturn upper stage and equip the stage as an orbiting laboratory. Between 1960 and 1969, the constant reengineering of this design to exploit new hardware surpluses enabled an even more robust vehicle to fly—one that could be launched into space as a complete, intact space station with little need for construction or maintenance in orbit, and for relatively little cost. Creating this vehicle, though, required both imaginative engineering and cooperation between NASA field centers, the leaders of which often had differing views on how to best accomplish NASA's goals (Fig. 8.1).[6]

The space station as a milestone in human space exploration is a concept older than human spaceflight itself. For much of the 1950s, von Braun had lobbied the American public for the construction of, among other vehicles, a large orbiting "wheel" station, whose slow rotation would provide artificial gravity for its crew, with a large internal volume that would make it a useful tool of scientific research, military applications, and further exploration of the solar system.[7] While Director of the

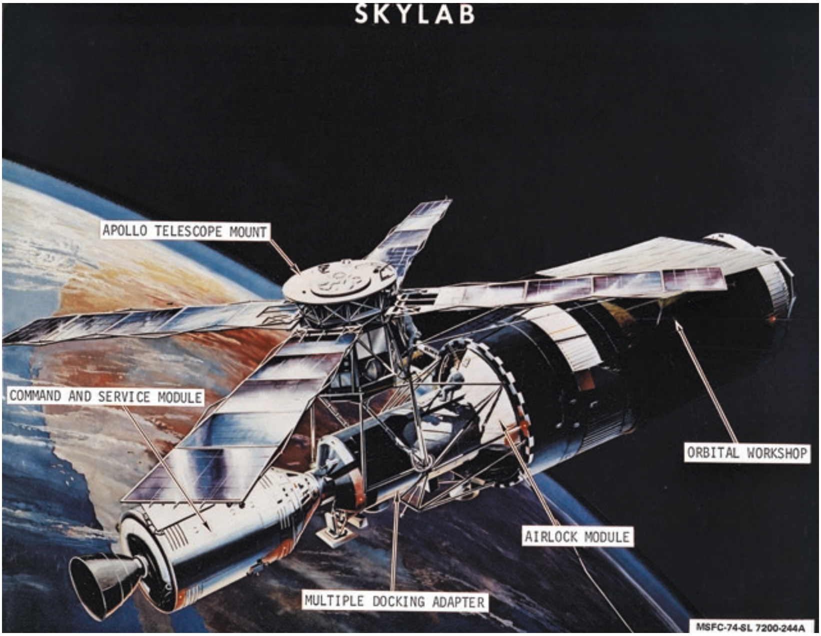

Fig. 8.1 The Skylab Orbital Workshop passes over Baja, CA in this Marshall Space Flight Center artist's drawing from 1974, depicting the station's actual configuration following the Skylab 3 crew's repairs. An Apollo command and service module is docked on the left, and the Apollo telescope mount is visible atop the vehicle. On the right, the two sun shades installed by the Skylab 2 and 3 crews are visible, one on top of the other. (NASA, image number MSFC-74-SL 7200-243A, public domain (Available at http://mix.msfc.nasa.gov/abstracts.php?p=1247))

Development Operations Division of the Army Ballistic Missile Agency at the Redstone Arsenal at Huntsville (the predecessor to MSFC), in 1959 von Braun supervised the development of Project Horizon, which imagined the use of discarded upper stages of a new class of heavy-lift launch vehicles—the antecedent to the Saturn I/IB—as a space station. The proposal called, initially, for the assembly of 22 of these upper-stage "shells," and, while the project would seem to require a great deal of organizational and technological acumen, the logic of fabricating a station in this way was almost undeniable, as it would be for the Skylab program that would follow it. Horizon (like Apollo) would produce an enormous amount of orbital "material … without a previously established purpose," and, like Apollo, Horizon was expected to utilize a "considerable fraction of foreseeable or predictable large booster resources," leaving no surplus launch capability available for orbiting a separate space station. "The economy of using otherwise wasted resources to a constructive end," the Horizon report's authors wrote, demanded the reuse of the upper stages to build a station.[8]

The early years of spaceflight in the USA and the Soviet Union were characterized by a mismatch between the ambitions of these embryonic space powers and the rudimentary lift capabilities of their launch vehicles, making von Braun's elaborate space stations too distant a goal to be realized in the near term.[9] A space station formed from a single upper stage might be feasible, though, once NASA's civilian effort to reach the Moon gave the USA the impetus to build von Braun's Saturn launch vehicle. Informal discussions between NASA and contractors concerning a spent-stage station likely occurred throughout 1960, and Douglas Aircraft completed a study on the reuse of the Saturn's liquid hydrogen/oxygen upper stage (the S-IV) in 1962, six years before Apollo flew and more than a decade before Skylab's launch.

The S-IV design would never become the basis for a space station, as NASA soon replaced it with the more powerful S-IVB upper stage. Constructed with a large liquid hydrogen tank providing 12,000 cubic feet of potentially habitable space (and a liquid oxygen tank able to serve as a waste container), the S-IVB constituted the second stage of the Saturn IB (or the third stage of the larger Saturn V launch vehicle), where it served to accelerate the Apollo command and service module (CSM) to orbital speeds. (As the upper stage would likely be complete before the Apollo CSM, Gemini craft would have docked with the spent-stage station.[10]) Although von Braun exercised considerable authority over its design as MSFC Director, the station that NASA launched in 1973 was the product of decision-making by a variety of NASA managers, including NASA Administrator James Webb, his successor Thomas Paine, NASA Deputy Administrator George Low, and Associate Administrator of the NASA Office of Manned Space Flight, George Mueller. As a result, Skylab ultimately bore little resemblance to von Braun's original Project Horizon concept. While von Braun had first lobbied for the reuse of an active stage or "wet" station, he later championed an alternative option: a "dry" station preconfigured at launch to operate in space without the need for propellant venting.[11]

Throughout the early 1960 s, it appeared likely that the success of the lunar program would leave at least one Saturn IB available as surplus, leading MSFC to design a wet station built around a repurposed S-IVB stage launched by NASA's smaller Saturn IB vehicle. When a surplus Saturn V became available in 1967, NASA found itself with enough lift capability to launch the S-IVB "dry," without fuel or engines and already equipped to operate as a station. Von Braun was not, at first, enthusiastic about this option (he originally preferred using the Saturn V's larger second stage to launch an even bigger "wet" station), but taking advantage of previous design work and available equipment made significant budgetary and technical sense. Von Braun also began to have doubts about the difficult construction work astronauts would need to do to convert the tank in orbit for habitation, swaying Mueller to the "dry" workshop concept for this reason.[12]

The eventual Skylab OWS itself was a hodgepodge of flown technology and leftover projects from AAP, including an airlock hatch derived from the Gemini spacecraft.[13] Some of the on-board equipment derived from early designs for a "wet" workshop assembled piecemeal by successive crews. Originally intended to be mounted on an Apollo lunar module (LM) in place of its descent engine, Skylab's Apollo telescope mount (ATM) conjured the general size and shape of the LM that was to carry it. Additionally, enough work had been done on the S-IVB "wet" station's interior fittings that the Skylab OWS retained artifacts of the previous design, including floors made out of metal honeycomb through which fuel could flow freely.

Other Apollo-era hardware was simply reused or minimally upgraded. The Apollo CSM could ferry astronauts to the station almost without modification, using the same probe-and-drogue docking assemblies and navigation systems used for the Moon program. Skylab's spacesuits were variants of the A7L suits worn by Apollo lunar crews. The suit's original modular construction meant that with the removal of lunar overshoes and backpack and the use of a simplified visor, astronauts could work outside the station as easily as they had surveyed the lunar surface.[14] Newer technologies were modest manipulations of Earth-bound technologies: space food had never been particularly palatable, and was improved for Skylab to more closely resemble traditional fare, including the use of more canned items. In-flight clothing, in keeping with the sartorial standards of the day, extended only as far as brown leisure suits and T-shirts (Fig. 8.2).

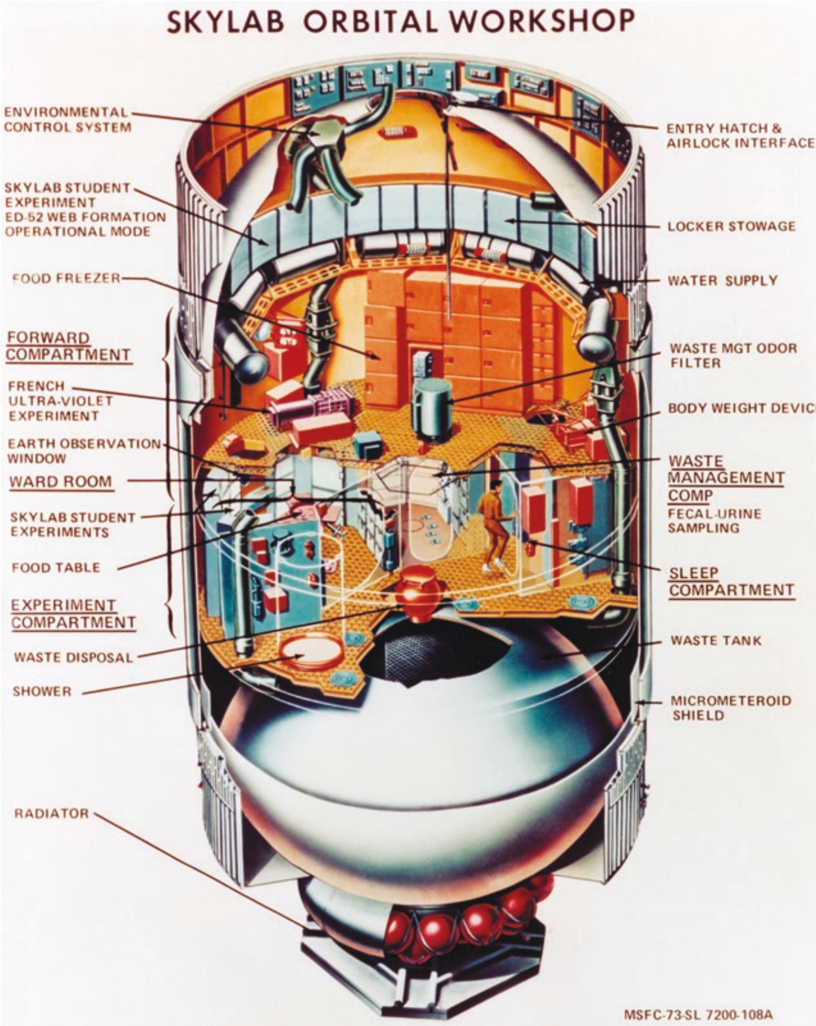

Fig. 8.2 The S-IVB liquid hydrogen and liquid oxygen tanks are visible in this cutaway schematic of the interior of the Skylab Orbital Workshop. (NASA, ID S73-23919, public domain (Available at https://images.nasa.gov/#/details-S73-23919.html))

Throughout Skylab's development, efforts to reuse existing technologies required flexibility to change the design in reaction to changes in resource availability, as well as design choices that offered capabilities so robust that even major changes would not require the redesign or retrofitting of basic components. Most importantly, it required several significant changes of opinion by leading engineer-managers, despite the considerable investment they had made in championing particular design philosophies. Rather than producing a space station with an assortment of poorly interacting components, the tangled design history of Skylab produced a sturdy craft that could absorb tremendous damage while remaining operational, as astronauts would soon learn.

Rescue Technologies for Skylab

The robustness of the eventual design would be tested on the unpiloted Skylab I launch, when a failure of the shroud protecting the station damaged the Skylab OWS, tearing off its protection against solar heating and micrometeorites and leaving it with most of its solar power panels torn off or folded up. Spacewalks by Skylab 2 crew members Pete Conrad and Joseph Kerwin not only restored most of the station's power, but rigged the first in a succession of replacement heat shields that lowered the station's ambient temperature and restored it to habitability. The tools for these repairs were clever, but not exotic. Simple cutting tools enabled astronauts to release a large solar array that failed to deploy, while the heat shields the astronauts installed consisted of gold-coated Mylar sheets stretched over the exterior of the OWS's habitable compartment. It was the reuse of simple materials, rather than the creation of new ones, that ultimately saved Skylab: on the Skylab 2 mission, astronauts carried a small, expandable sun shade that could be deployed and unfolded through Skylab's scientific airlock like an umbrella, without the need to venture outside. A second, larger shade carried by the Skylab 2 astronauts was installed by the Skylab 3 crew.

Throughout the next year, NASA engineers and astronauts adapted to Skylab's deficiencies while extracting from it virtually all of its capabilities in solar astronomy and Earth resources photography. Ultimately serving as a "house in space" for three Apollo crews (with the final mission lasting 84 days), Skylab continued to challenge astronauts and ground crews, particularly on the second piloted visit, Skylab 3, when thruster problems with the Apollo ferry vehicle that the astronauts had flown to the station suggested that a rescue mission might be necessary. While a mission to rescue the potentially stranded crew was never flown, NASA, in a relatively short period of time, assembled a viable rescue craft from its proven Apollo CSM, stretching its capabilities in remarkable ways, and demonstrating a viable on-orbit rescue capability.

As with the development of Skylab itself, the creation of a Skylab rescue vehicle began as a contractor study, when engineers at North American Aviation (NAA, the prime contractor for Apollo) recommended production of a modified Apollo vehicle equipped with four crew couches instead of the usual three to rescue astronauts stranded in lunar orbit.[15] The rescue craft would be produced alongside regularly configured Apollo CSMs, and placed on standby for use in the event of a mission emergency, at which time a lone astronaut would fly the vehicle to the Moon and recover the stranded crew. The cost of the rescue vehicles would have been considerable, though, and NASA chose not to develop them for the Moon landings. NAA and NASA, however, rehabilitated the rescue concept for Skylab, though in a manner that made greater use of existing hardware and would not require the construction of a dedicated rescue craft.

Instead, the Skylab rescue mission, or SL-R, would consist entirely of a conversion kit that launch-pad engineers could use to replace the seating on any existing Apollo CM with five crew couches, easily accommodating both the two-person SL-R mission crew and the three rescued Skylab astronauts. Instead of designated a specific rescue launch vehicle, the next Apollo CSM and Saturn IB ferry rocket in line for launch would be reconfigured for rescue operation, ensuring maximum response speed and minimal disruption to normal pad operations. NASA's 1972 NASA mission requirement report stated:

> The CSM/Launch Vehicle (LV) system including CSM 119 and LV 209 shall continue in a normal state of launch readiness preparations for the nominal Skylab mission until a decision is made to proceed with preparation of the SL-R mission; then, modification of the CSM and total systems preparation for launch readiness shall be accelerated to the maximum extent practical.[16]

When thruster problems appeared on Skylab 3, backup crew members Vance Brand and Don Lind immediately began training to recover the potentially stranded astronauts. Skylab's multi-month supply of air, food, and water nevertheless reduced the urgency of the rescue, and when subsequent work by astronauts and ground engineers determined that malfunctions would not jeopardize the Skylab 3 crew, NASA canceled the rescue flight. Given the extent of NASA's preparations, though, the SL-R mission's success appeared likely. NASA would not develop a similar on-orbit rescue capability for another 30 years, following the loss of the space shuttle orbiter *Columbia*.

From Apollo–Soyuz to International Skylab

American astronauts had never truly been alone in space. At the same time as Apollo vehicles flew, Soviet Soyuz spacecraft were in space as well, leading planners and popular authors to imagine rescue scenarios involving spacecraft of multiple nations. In practice, such rescues would have been extremely difficult: American and Soviet spacecraft operated in different orbits, and the velocity change required to alter their trajectories would have been beyond the capability of early spacecraft. Built for travel to the Moon and back, Apollo hardware nevertheless possessed the necessary power. NASA's Saturn family of launch vehicles had lifting power to spare, while the service propulsion system (SPS) on-board the Apollo CSM was designed for lunar orbit insertion and trans-Earth engine firings, giving it a surplus of power for Earth-orbit operations. NASA would next harness these capabilities in its 1975 joint flight with the Soviet Union. The Apollo–Soyuz Test Project (ASTP), in which American astronauts and Soviet cosmonauts met in space for the first time (and the last time for twenty years), demonstrated the flexibility of the Apollo–Saturn system, and pointed to an alternative architecture of international space exploration (Fig. 8.3).

The genesis of the ASTP mission lay in efforts to improve US–Soviet political relations after the conclusion of Nikita Khrushchev's confrontational term as General Secretary of the Soviet leadership. In the USA, though, popular culture had already explored the possibility of joint US–Soviet operations in space, particularly within the context of orbital rescue, which had been the subject of *Marooned,* a 1964 novel by Martin Caidin and its 1969 film adaptation. The story imagined Soviet cosmonauts coming to the rescue of an American craft stranded in low-Earth orbit (the scenarios for which NASA would develop the Skylab rescue mission capability).[17] NASA Administrator Thomas Paine proposed a joint flight with the Soviet Union in 1970, but the proposal at first met with little interest

Fig. 8.3 This April 1975 NASA artwork by Davis Meltzer depicts a cutaway view of the international spacecraft created by the Apollo–Soyuz Test Project in July of that year. On the left, two American astronauts leave their crew mate in the Apollo command module to enter the docking adapter and meet their two Soviet cosmonaut counterparts in the Soyuz. NASA considered a follow-on mission that would have entailed joint US/Soviet operations aboard a successor to the Skylab Orbital Workshop. (NASA, image number S75-27290, public domain (Available at https://images.nasa.gov/#/details-S75-27290.html))

among Soviet officials, until Philip Handler, President of the National Academy of Sciences, explained the plot of the recent American science fiction film *Marooned* to Soviet Academy of Sciences President Mstislav Keldysh and his staff. Impressed that the American public would accept the notion of "a Soviet cosmonaut as the hero who saves an American's life," their opposition to the mission evaporated.[18] NASA and the Soviet Academy reached an agreement regarding the mission in 1972; following training exchanges between the American and Soviet crews, the mission launched three years later.[19]

Ultimately, it was Apollo's flexibility that enabled the mission to be successful. The Soyuz spacecraft typically launched into an orbit inclined more steeply than that of its American counterpart, and, because the Soyuz lacked sufficient propulsion capability to change its orbital plane, arriving at the rendezvous orbit was to be NASA's responsibility, along with the design, construction, and launch of a docking adapter to facilitate pressurized crew transfers between the vehicles. Once again, hardware intended for lunar operation demonstrated enhanced capabilities, this time as an international orbital ferry.[20]

Despite initial difficulties, the ASTP mission proved successful, and showed that in the future, even more ambitious joint operations might be possible. Skylab, orbiting empty since 1974, presented such an opportunity. Plans to internationalize Skylab by opening it to Soviet spacecraft were not explored, nevertheless. NASA, recognizing its technological superiority, feared the worst of its Soviet counterpart and was particularly apprehensive about unchaperoned cosmonaut visits to Skylab.[21] After the success of ASTP, NASA's attitude toward joint operations softened, however, and informal planning resumed. While the first Skylab OWS had limited remaining supplies of oxygen and other consumables onboard, a second OWS constructed as a back-up to the first station (later designated "Skylab B" or "Advanced Skylab") could be flown on another surplus Saturn V. Once in orbit, the station would serve as a destination for both Soviet and American crews.[22] Ultimately, NASA chose against flying a second Skylab, preferring to devote funding to the space shuttle program and its planned construction of a later, larger space station concept.

Skylab in the Shuttle Era

Among the tantalizing arguments in favor of launching a second Skylab was the likelihood that it would remain in orbit long enough for early space shuttle crews to visit and augment it, creating a shuttle-era international space station at least twenty years before the International Space Station. When NASA shelved the proposal to launch Skylab B, it continued to explore ways to inexpensively extend the life of the original Skylab, which remained in orbit and functioning as the shuttle neared completion. One 1978 McDonnell Douglas study that was typical of these proposals detailed a series of space shuttle flights through 1984 that would augment Skylab's power-generating capabilities and habitable volume, providing "[g]rowth and continuously manned operations" for the foreseeable future. Unlike Apollo flights, which NASA planned around specific mission objects, shuttle missions to the versatile space laboratory could be folded into existing budgets, promising economic efficiencies throughout Skylab's later life.[23] The study's authors wrote:

> The most significant conclusion to be drawn from the reuse study is that Skylab [is] in remarkably good condition and can be returned to operational capability in conjunction with the STS program for an investment of about 50 million dollars. Thus, Skylab offers the most economical and cost-effective means for NASA to activate an operational space station in the near future.[24]

For this expansion to occur, though, NASA would need to ensure that Skylab remained in orbit until the shuttle was ready to fly. During the late 1970s, however, greater than expected solar activity expanded the Earth's atmosphere and increased the drag on Skylab enough to threaten its orbit. NASA planned two options for raising Skylab's orbit. The first would again use the Apollo CSM in a manner in which it had never been intended: as a reboost vehicle, using its SPS to nudge Skylab into a higher orbit. One of NASA's three remaining Saturn IB vehicles would launch an Apollo CSM to dock with the empty Skylab and fire its service propulsion system to raise the station to a higher orbit. (If that course of action proved unworkable or undesirable, the crew would instead lower Skylab's orbit so that it could reenter the atmosphere more safely and on a trajectory unlikely to impact a populated area.) Astronauts Vance Brand, Don Lind, and Bill Lenoir would have flown the reboost mission, which would have been accompanied by a short stay in the station for scientific work. The more hazardous de-orbit mission would have flown only Brand and Lind: the mission profile would have forced the two to fire the SPS, undock, and withdraw from Skylab within a matter of minutes to avoid de-orbiting themselves along with the station.[25]

NASA ultimately rejected both options for cost and safety reasons, planning instead to launch aboard the second space shuttle flight an unpiloted propulsion module, the Teleoperator Retrieval System (TRS), manufactured by contractor Martin Marietta (Fig. 8.4). Shuttle

Fig. 8.4 This 1978 artist's conception depicts the Teleoperator Retrieval System being used to boost Skylab into a higher orbit, following the systems release from the space shuttle's cargo bay, on the left. The reboost mission was scheduled for 1979, but was never flown. (NASA, image number S78-23630, public domain (Available at https://images.nasa.gov/#/details-s78-23630.html))

astronauts would carry the TRS into orbit in the shuttle's cargo bay, and dock it remotely to Skylab before using its strap-on rockets to propel the station to a safer orbit.[26] Delays preparing the shuttle for its first flight, however, doomed the plan. The first shuttle orbiter, *Columbia*, did not fly until 1981, two years after Skylab's orbit fatally decayed. Despite NASA's efforts to direct its debris into the Indian Ocean, significant debris struck a sparsely populated region of Western Australia.[27] Skylab's demise, though, resulted less from astronomical misfortune than a budgetary decision to shift funding from Skylab to NASA's new spaceflight infrastructure. Had NASA committed to reboosting the station, it most likely would have survived well into the 1980s.

Assessing NASA's *Bricolage*

For a brief period after the first successful Moon landing of Apollo 11, NASA's attention turned toward Skylab as the agency's best hope for stoking popular interest in space travel. NASA Deputy Administrator George Low wrote to President Nixon's Science Advisor Edward E. David in 1970 that further Moon landings were unlikely to provide "major new opportunities for international leadership and prestige." Skylab, though, in which NASA had already made a "considerable investment," offered the promise of new adventures and international cooperation.[28] Four years later, NASA's experience with Skylab had demonstrated the capabilities of repurposed hardware, while the ASTP flight the following year opened the door to the kind of international cooperation Low had eagerly sought. No other American space station project, furthermore, did so much for so little. As a program to orbit astronauts for an extended period of time in a well-stocked space laboratory, the Skylab OWS proved ten times less expensive to build and operate than the International Space Station, its nearest American analog. Skylab cost approximately $2.6 billion ($15.6 billion in 2014) to build, launch, and operate; the International Space Station is expected to well exceed $150 billion by the time of its retirement. Skylab's costs also closely matched initial estimates; in 1970, the Government Accounting Office estimated Skylab's total cost to be with 10% of the actual eventual figure.[29]

While highly successful, however, NASA's reuse of Apollo hardware during the 1970s was only a partial demonstration of the agency's capabilities. At the conclusion of the Skylab and Apollo–Soyuz programs, NASA still possessed an additional Skylab OWS, three Apollo CSMs, two Apollo LMs (which could have been repurposed as on-orbit space station modules), and five assorted Saturn launch vehicles, including two Saturn Vs. The end of production lines for these vehicles would have limited any program that made use of this equipment, but by this time NASA had already demonstrated that even orphaned craft could provide value when properly reconfigured for new uses. (Indeed, one elaborate mid-1960s NASA study transformed the S-IVB into an interplanetary flyby craft on a mission to Venus.) Instead of flying in space, though, the unused vehicles became popular museum displays. While their demise was vexing to astronauts,[30] it ironically demonstrated yet another potential transformation of Apollo's versatile hardware: from flight vehicles to educational tools, studied and enjoyed by generations of historians and members of the general public. This use was not the one that NASA and its contractors had envisioned, nevertheless.

Assessments of decisions by NASA and the Nixon Administration to move away from Apollo have commonly cited the space shuttle program as the principal factor in the debate: the expensive new architecture for piloted flight would likely have required the entirety of NASA's human spaceflight budget, leaving nothing for dead-end programs despite their demonstrated success.[31] The choice, however, was not between two competing spaceflight architectures, but between the presence and absence of a defining infrastructure for exploration. A commitment to a particular design infrastructure—Project Apollo—marked NASA's first decade; NASA ultimately subordinated all human spaceflight activities to the needs of Apollo, and suppressed other vehicles (including derivatives of the Gemini spacecraft) to avoid budgetary competition for Apollo's objectives. Under Webb's stewardship, NASA produced this infrastructure, but it was clear to him by 1969 that no clear mandate existed for anything following Apollo. That left his subordinates, like von Braun, Low, and Mueller, to plan how they could squeeze whatever capabilities they could out of NASA's post-Apollo hardware. As W. David Compton and Charles D. Benson note in *Living and Working in Space: A History of Skylab*:

> George Mueller saw an imperative in NASA's founding legislation: to build and maintain an unexcelled capability to operate in space for the national interest. Under that axiom he could not envision allowing the Saturn-Apollo technological accomplishment to be dissipated. If no clear mandate was forthcoming, then utilization of that enormous investment was mandatory until the next step could be defined. When the time came to keep that capability alive, the wet workshop was what Mueller had and he determined to make the best use of it. As circumstances changed, he adjusted his program—postponing launch dates, trimming the experiment program, reducing the number of flights, shifting the work load between centers—to make the best use of his resources.[32]

Because Apollo hardware had been designed from inception with an eye toward enlightened modification and reuse, it proved particularly amenable to this approach.

In January 1972, NASA sought to replace the Apollo infrastructure with another (the space shuttle), but the decision did not end questions about the value of a massive flight infrastructure. The space shuttle would not be available in time to meet NASA's exploration needs of the 1970s, and might not even be able to accomplish them if it was, absent additional hardware. In addition, some within NASA worried that tying the agency to the creation of elaborate infrastructures doomed it to obsolescence. In 1973, NASA Assistant Administrator for Public Affairs John Donnelly wrote to then NASA Administrator James Fletcher, cautioning him that "The more I think about it, the more convinced I become that … we've got to arrive at an agency rationale and get away from the project-oriented mode, wherein we spend time, money and effort emphasizing projects that quickly become obsolete."[33] The temptation to build space exploration programs around novel architectures is a powerful one (and, indeed, contributed to AAP's success), but not every exploration goal requires radical paradigm shifts in vehicle design. Rather, throughout the 1970s NASA demonstrated that spaceflight technology innovation sometimes occurs best piecemeal, in response to actual mission needs, and that it should treating hardware that exists today as more valuable than better technologies available five years from now.

Conclusion

When Skylab 2 astronauts Pete Conrad and Joseph Kerwin stepped out of the OWS in 1973 to repair the station's crippled solar panels, they did so as astronauts selected during previous space programs (Mercury and Gemini)—one a naval test pilot and the other a medical doctor. To repair a space station carved out of a repurposed launch vehicle upper stage, they traveled in a capsule first designed in 1961 while wearing a spacesuit intended for use on the Moon, and exited through a hatch borrowed from a spacecraft last flown in 1966. The tools that ultimately fixed their space station, furthermore, ranged from a novel collapsible sun shade to a hammer and a pair of pruning shears, neither of which looked at all remarkable.[34]

Project Skylab, in particular, demonstrated that when confronted by specific requirements and limitations, organizations can innovate in surprising ways, and that many of the most robust solutions are also the simplest. Given the tendency of large organizations to favor the most complex solutions to problems, NASA's efficient utilization of existing hardware represented a triumph over institutional pressures to develop novel solutions to every problem. Rather than an ability to imagine entirely novel vehicles, the spaceflight engineer's most valuable skill is flexibility in leveraging existing infrastructures, regardless of personal or institutional preferences. Ultimately, the organizational apparatus that sent Americans to the Moon was capable and flexible enough to tackle other projects with lean resource budgets, by innovating through repurposing and reuse of hardware that was well engineered to begin with.

In his 2007 book *The Shock of the Old: Technology and Global History since 1900*, David Edgerton writes that despite the excitement surrounding the invention of exotic new technologies, older alternatives tend to persist in regular use far longer than most people would imagine.[35] Rather than representing a failure of the inventive process, this fact demonstrates that much of engineering practice involves the maintenance, reuse, and repurposing of older, more robust technologies, and that this effort often makes strong economic sense, even in an age of high technology. By repurposing surplus hardware to fabricate a space station, NASA demonstrated that the most valuable attribute of human spaceflight technology is flexibility, rather than the achievement of specific goals. While not all of NASA's efforts to operate and extend the life of Skylab were successful, they demonstrated that every program of exploration does not require an entirely new exploration infrastructure. The robustness of Apollo's essential components—the Saturn V launch vehicle, the Apollo CSM, the A-7L spacesuit, and the procedures for training and managing crews—was sufficient for multiple missions outside of the original intentions of those who designed these technologies. And in a field of technology punctuated by what Edgerton describes as a false "futurology of the past,"[36] it is technologies that confound our understanding of the "new" that often prove most effective.[37]

Notes

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4. Barton C. Hacker and James M. Grimwood, *On the Shoulders of Titans: A History of Project Gemini*, *NASA SP-4203* (Washington, D.C: NASA, 1977), 117–20.
5. Hacker and Grimwood, *On the Shoulders of Titans*, 364–65.

6. See, e.g., David J. Shayler, *Skylab: America's Space Station* (Chichester, UK: Praxis, 2001); W. David Compton and Charles D. Benson, *Living and Working in Space: A History of Skylab*, (Washington, DC: NASA, 1983).
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9. See, e.g., W. David Compton and Charles D. Benson, *Living and Working in Space: A History of Skylab* (Washington, DC: NASA, 1983), 26.
10. NASA Technical Memorandum December 1974 MSFC *Skylab Extravehicular Activity Development Report* Skylab Program Office MSFC—Form 3190 (Rev June 1971), 3.
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23. McDonnell Astronautics Company, *Skylab Reuse Study Final Report and Reference Data, Volume I* (Huntington Beach, McDonnell Douglas, 1978), 6–7.

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CHAPTER 9

Encouraging New Space Firms

John M. Logsdon

On September 16, 1991, President George H. W. Bush, accompanied by Secretary of Commerce Robert Mosbacher, presented the National Medal of Technology to the Pegasus launch team of the Orbital Sciences Corporation (Fig. 9.1). The citation accompanying the medal read: "For their invention, development, and production of the Pegasus rocket, the world's first privately-developed space launch vehicle that has opened the door to greater commercial, scientific, and defense uses of space."[1] At the time of the presidential award, there had been two launches of Pegasus, an innovative air-launched small rocket designed to carry lightweight payloads into orbit. The rocket was the second product of Orbital, a company founded less than a decade earlier by three young entrepreneurs soon after they graduated from Harvard Business School. Without support from NASA, Orbital would likely not have survived that decade; it had been a NASA–Orbital partnership that enabled the new company to get started and to be in a position to initiate the Pegasus project. Remarkably, Pegasus had been developed in less than three years from the time it was first conceived to its initial flight in April 1990. Not only was the launch vehicle innovative, so too was the company that developed it.

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Fig. 9.1 President George H. W. Bush (second from *right*) presents the National Medal of Technology to David W. Thompson (third from *right*), September 16, 1991. Also in the photograph are Pegasus program manager Antonio Elias (*right*) and Secretary of Commerce Robert Mosbacher (*left*). (Courtesy of Orbital ATK Corporation.)

The presidential award was just the latest in a series of recognitions of Orbital as a role model of a successful entrepreneurial space company. In 1989, Orbital had won the DARPA Outstanding Technical Performance Award, the American Astronautical Society Space Commerce Award, and the Space Foundation Commercial Space Award. These honors had been followed in 1990 by the National Air and Space Museum Trophy, the National Space Society Space Pioneer Award, and the Space Business Roundtable Commercial Space Industry Award, among other recognitions. From its beginning in 1982 as the brainchild of three under-30 space entrepreneurs who invested a total of $1500 in starting the company, Orbital had by the end of 1990 grown into a firm with over 700 employees and $100 million in annual revenues. It was also the first entrepreneurial space firm to "go public";

an initial stock offering in the weeks following the first Pegasus launch was heavily subscribed.

The success of Orbital would have been difficult to forecast as what was then called the Orbital Systems Corporation was incorporated on April 2, 1982. (The original target had been April Fool's Day.) At that point the company was little more than a mailbox address in Chicago and a telephone answering service—plus an idea for a new space business. The incorporators were three young men who had met as they pursued graduate studies at Harvard Business School. In April 1982, David Thompson was 28 years old, Scott Webster, 29, and Bruce Ferguson, 27. Each had contributed $500 as their initial investment in the new firm. The company's first business plan, prepared three weeks later, stated that the firm's objective would be "to design and market a liquid-fueled, high-performance, potentially reusable orbital transfer vehicle for use with the Space Shuttle."[2] The new corporation was to be a technically based management, marketing, and financial company; it would not, at least at its outset, engage in manufacturing space hardware.

As its statement of purpose suggests, the success of Orbital would be linked at the company's inception with NASA and its Space Shuttle, which had had its first flight a year earlier. Without NASA's support, particularly in its early years, it is not clear that Orbital would have survived to be the beneficiary of numerous honors a decade later and to be the first private-sector firm to develop a space launch vehicle as its second product line.

The creation of Orbital came at a time of increased emphasis on the commercial development of space. The November 1980 election of Ronald Reagan as President and a Republican Congress brought to Washington a number of individuals committed to what Andrew Butrica characterized as the "conservative space agenda," one which favored business interests in space over objectives such as space science and exploration.[3] Some adherents of this agenda adopted the libertarian perspective that the appropriate role of government in space should be very limited, focusing on creating a permissive policy and regulatory climate within which private space activities could thrive, while minimizing government-funded space efforts. Others took a more measured approach, advocating an increased emphasis on commercial space activities within the government policy framework and encouraging NASA, as it carried out the government's civilian space efforts, to collaborate more closely with the private sector in commercially oriented space developments.

This latter perspective provided a fertile climate within which initiatives such as that proposed by the Orbital founders could take hold. While NASA at times struggled to adapt to its new relationship with the commercial space sector, its interactions with the emerging Orbital were positive and ultimately productive.

Early Years[4]

The connection between NASA and the three Orbital founders actually went back even to before the company's inception. Thompson and Webster had met in 1979 when they began their MBA studies at Harvard Business School; the two met Ferguson a year later when they all participated in a NASA-funded "creative marketing strategy field study" that was part of their second-year curriculum. The focus of the field study, as mandated by NASA, was materials processing in space, and particularly the opportunities for and barriers to its commercial success. That study provided the opportunity for a seven-person study team to familiarize themselves with the space sector, traveling to NASA installations and aerospace and other firms as they pursued their research. Of the three members of the team who would stay together to found Orbital, Thompson was the only one with a space background: he had engineering degrees from MIT and Caltech and had been working for NASA on the space shuttle before enrolling at Harvard. Webster also had an engineering degree, but had not been working in the aerospace sector. Ferguson was completing a joint law and business degree program; his undergraduate degree, also from Harvard, was in government.

After graduating in June 1981, the three went on to new jobs, but stayed in close touch. As an undergraduate at MIT in the mid-1970s, Thompson had thought that someday he would like to found his own space company, but it was Ferguson, as he and Thompson shared breakfast a few weeks before graduation, who "first articulated the idea that starting a space enterprise was something we could actually do … and sooner rather than later." Throughout 1981, the three continued their search for the right business opportunity. In October of that year, six of the seven authors of the Harvard paper traveled to Houston; their paper had received an award for academic contributions to commercial space activities from the Space Foundation. At the award ceremony, they met Space Foundation's executive director Sam Dunnam, who encouraged them to act on their dream by actually starting a space business, and Fred Alcorn, a wealthy oil tycoon. Alcorn was particularly impressed by Thompson and expressed his willingness to invest in a space start-up, should Thompson and his colleagues actually move in that direction.

The focus of the continuing discussions during 1981 between Thompson and Ferguson was identifying a space product or service around which they might organize a business venture. At one early point Thompson suggested finding a way to use the space shuttle's unused weight-lifting capability on each mission to haul water into orbit, where it could be stored and eventually transformed into rocket fuel; that idea was quickly abandoned as too visionary. Their work at Harvard had convinced Thompson, Ferguson, and Webster that the business potential of materials processing in space was also years in the future. It was clear, however, that there was a large and fast-growing market for communications satellites, and that the space shuttle was likely to be the launcher of choice for many private-sector firms wanting to get such satellites into space, given the very attractive prices that NASA was offering to commercial users of the shuttle's launch services (see Chap. 7). They also recognized that there would necessarily be a demand for the upper-stage rockets needed to transfer communications satellites from the shuttle payload bay in low-Earth orbit to geostationary transfer orbit (GTO) and ultimately to their final destination 35,800 kilometers (22,300 miles) above the Earth's equator. Such a transfer stage fit with another conclusion from the Harvard study: that it would be difficult to develop a specific "winner" in commercial space activities, and thus that it was better to focus on identifying an element of the service infrastructure needed to support the competition among various space product providers, in this case owners of various communication satellites. By early 1982, the three had converged on a shuttle-based transfer stage as the ideal initial product for their newly formed company; that convergence was reflected in Orbital's April 1982 business plan.

The question then was what kind of transfer stage to develop. The established aerospace firm McDonnell Douglas had already developed "payload assist modules" to carry lighter payloads (1,000–3,000 pounds) to GTO. The Air Force was developing an inertial upper stage (IUS) for transferring 3000–7000 national security payloads; that vehicle would also be used for civilian and commercial satellites. For heavier payloads in the 7000–12,000 pounds range, NASA was planning to modify an existing upper stage called Centaur for use with the shuttle. The Centaur had been developed for use with the Atlas expendable launch vehicle. NASA was having trouble getting White House and Congressional support for funding the proposed modification. While there were few communication satellites that heavy in development, the Orbital team anticipated that there would be weight growth in the future as such satellites became more complex, and in the interim there were a number of heavy NASA and national security payloads for which a Centaur-class upper stage would be needed.

This seemed to be the opportunity for which the Orbital founders were looking. Thompson and Ferguson decided to incorporate a new space company and invited Webster to join them. As they incorporated their new venture, the three anticipated that they would propose to NASA that their new company would raise from private investors the funds needed to finance the design, development, and testing of a shuttle-compatible Centaur. However, as Thompson recounts:

> NASA did not react as we expected. Because of the Centaur's importance to high-value planetary exploration and national defense spacecraft to be launched from the Shuttle, the space agency could not depend on a new, unproven company to fund and manage its development. Instead, just as we were putting the finishing touches on our formal proposal for a private/public partnership to create the Centaur OTV [orbital transfer vehicle], NASA's congressional allies allocated funds … for a government-run Centaur program. So much for our first space product!

As they were developing their proposal for NASA, Thompson, Ferguson, and Webster had also been "making the rounds" of the Washington space community. The three were clearly intending to work within the existing space policy framework rather than pursue an outsider path. They found support for their overall initiative from NASA Administrator James Beggs and his associate Llewellyn (Bud) Evans, who in turn introduced them to individuals in the Reagan White House interested in space commercialization, such as assistant to the president Craig Fuller and his staff. They also interacted with the Office of Management and Budget and the Office of Science and Technology Policy. The White House was in the process of preparing a new statement of national space policy; when that policy was released on July 4, 1982, it stated that "the United States encourages domestic commercial exploitation of space capabilities, technology, and systems for national economic benefit."[5]

The three founders also visited Air Force officials and members of Congress and their staff.

Given this careful cultivation of support and the obvious enthusiasm and sense of competence with which the three young entrepreneurs presented their plans, it is not surprising that "NASA let us down gently" with respect to a commercially developed Centaur. Thompson would later comment that NASA "was more encouraging and helpful than anyone would have the right to expect." The Orbital team met with NASA Associate Deputy Administrator Phil Culbertson in July 1982; he urged them to keep working on a business plan for a product other than Centaur. Culbertson indicated that "for the right project, NASA would be prepared to enter a joint venture with our newly formed company." Culbertson also made what turned out to be a fateful suggestion: that the Orbital team should meet with Dr. Jack Wild, NASA's expert in orbital transfer vehicles, to explore alternative possibilities for an initial product. It was Wild who would identify the alternative product that they were seeking.

The Transfer Orbit Stage (TOS)

However, before the Orbital founders could begin serious discussions with Wild at NASA, they faced a crisis threatening their ability to continue with their venture. They were almost out of money. Thompson, Ferguson, and Webster had stayed on in their post-graduation jobs while promoting their new company on a part-time basis, but they were close to maxing out their credit cards and had exhausted other sources of personal finance. Remembering Fred Alcorn's suggestion of the previous October that he might be willing to invest in their space start-up, the three journeyed to Houston in August 1982 to meet with Alcorn and Dunnam. On the morning of their meeting, the two men listened to their presentation, liked what they heard, and told Thompson, Ferguson, and Webster to come back after lunch with a specific investment proposal. After some hurried calculations on a napkin as the three ate lunch in a delicatessen in the basement of Alcorn's building, they presented their proposition. Alcorn "agreed in principle to the financing on the spot." With seed capital of $250,000, which Alcorn called "walking around money," the Orbital initiative could continue.

Thompson, Ferguson, and Webster, "with operating funds in hand and credit cards paid off," were ready to restart their search for a new product.

The Air Force IUS intended to lift medium-weight payloads from the shuttle to higher orbits was turning out, in order to meet national security requirements, to be a complex and expensive piece of hardware. NASA's Jack Wild had commissioned an exploratory in-house study of a less complex and less expensive alternative to the IUS, and, when the results of that study were promising, was planning a NASA-funded competition for the preliminary design of that alternative. He designated this concept the transfer orbit stage (TOS). By this time, the European Ariane expendable launch vehicle had launched its first commercial payload, a US-owned communication satellite, and Arianespace, the company set up to manage and promote the vehicle, was aggressively marketing Ariane's services in direct competition with the space shuttle. Having available a less expensive upper stage like the TOS would help the shuttle in that competition. Not only NASA but also the White House and Congress were determined not to allow the European rocket to capture a large share of the global, much less the US, commercial launch market.

The Orbital team first heard of the TOS concept when in October 1982 they attended an AIAA conference in Washington, at which Wild presented a paper on the concept. The TOS seemed exactly the kind of product they were seeking to develop, and they quickly scheduled a meeting with Wild to suggest that Orbital could develop the TOS on a commercial basis, given only that NASA would agree not to use government funds to develop a competing product. Thompson also wrote to Wild's boss, NASA Associate Administrator for Space Flight James Abrahamson, an Air Force Lieutenant General, setting forth the arguments for giving the company the exclusivity they wanted. Wild, wanting to make sure that a transfer stage would be available when NASA needed it in a few years, was skeptical about Orbital's capabilities and financing, but he and Abrahamson agreed to give it an opportunity to make its case. He told the Orbital team to prepare a presentation for him and his associates.

That presentation took place at NASA Headquarters on December 9, 1982.[6] By this time Orbital had hired its first two employees and, to give additional gravitas to the company, had added as a consultant the respected German émigré engineer Krafft Ehricke. In its presentation, the Orbital team discussed its business strategy and provided a detailed analysis of the future communications satellite market. That analysis suggested there were 26 missions between 1986 and 1990 for which the transfer vehicle they were proposing could qualify. The technical concept presented to NASA was based on the solid rocket motor being developed for the first stage of the IUS; it was designated SRM-1X and described as a “simple, inexpensive system” that could be used with both the space shuttle and the most powerful existing expendable launch vehicle, the Titan 34D; it could launch some NASA planetary exploration and other science missions as well as communication satellites. They proposed that the vehicle would be “commercially funded at no cost to government,” as long as “NASA grants OSC exclusivity to the vehicle,” and that the first vehicle would be ready for use with the space shuttle by the end of 1986.

The Orbital presentation emphasized that the company would provide only financing, marketing, and systems management of transfer stage development; actual engineering and manufacturing work would be carried out by an established aerospace firm. Over the preceding months, the Orbital founders had been discussing such an arrangement with potential hardware suppliers, while also contacting potential customers for the transfer stage and presenting their plans to a variety of government organizations. They had clearly done their homework, and had found no “red flags” as barriers to their ideas.

Wild and his associates went into the December presentation skeptical that it would convince them to take a chance on the new company, but the quality of the presentation changed their mind. They decided to give Orbital a chance to show it could deliver on its promises before pursuing the alternative of a government-funded competition to develop a TOS. On December 17, NASA and Orbital signed a Memorandum of Understanding (MOU) to begin discussions of “the commercial development of a new upper stage to be used with the Space Shuttle.”[7] This was merely an agreement to discuss a future agreement; it committed NASA only to listening to a detailed proposal from Orbital.

Although NASA signed the MOU, Wild and his associates were still proceeding cautiously. They gave Orbital only six weeks to demonstrate that it was capable of taking on the transfer vehicle’s development before embarking on a government-funded study of the TOS concept. Thompson suggested: “if we failed, the deal was off and our fledgling enterprise would probably sink without a trace.” The “swim or sink” presentation to NASA was scheduled for January 24, 1983.

As noted above, while they prepared their presentation to NASA the Orbital founders had been working with established aerospace companies to identify the best candidate for actually building a transfer stage. With the signing of the December MOU, Thompson, Webster, and Ferguson were sufficiently optimistic to quit their post-graduation jobs and devote all their time to preparing for the January 24 meeting with NASA. They had tentatively identified Martin Marietta as the best company for the hardware development role, and hoped that it would invest some of its own funds in a joint venture to design and manufacture the transfer stage. The Martin Marietta engineering team was led by a young vice president named Peter Teets, later to be a senior government space official. He and his associates were interested in working with Orbital, but as a funded contractor, not as a cost-sharing partner. They so informed Orbital on December 23. Discussion with other potential partner firms continued over the next few weeks, but Martin Marietta remained the preferred supplier. Finally, on January 21, just three days before the NASA presentation, Orbital relaxed its co-investment requirement, and Martin Marietta agreed to take on a fixed-price contract for TOS design and development and to support Orbital at its January 24 presentation.

In parallel with identifying its technical partner, Orbital also had to demonstrate that it had access to the financial resources required to begin TOS development. The signing of the MOU with NASA led Alcorn and Dunnam to make another investment of up to $2 million. Alcorn also secured for Orbital a $2 million line of credit with his bank, a resource which the company never had to use. Former NASA Administrator Thomas Paine provided additional capital as a third investor. Alcorn would later comment that Thompson "really turned me on. I didn't invest in TOS. I invested in those three guys."[8] Ferguson, who was spearheading the company's financial and legal affairs while Thompson concentrated on engineering issues and Webster on market development, also made contact with several venture capital firms that had a potential interest in investing in Orbital.

The January 24 presentation to NASA was a success. Alcorn and Dunnam spoke of their confidence in the Orbital team and the importance of encouraging American entrepreneurs. Teets from Martin Marietta and his team gave a strong technical presentation. Orbital's Thompson suggested that a NASA agreement to support the commercial development of TOS would establish an important precedent in implementing the Reagan Administration's policy of encouraging space commercialization, could shift up to 14 payloads from Ariane to the space

Fig. 9.2 NASA Associate Administrator Lt. General James Abrahamson (*left*) and Orbital's David Thompson (*right*) as they signed the April 18, 1983 agreement that cleared the path for Orbital to develop the TOS on a commercial basis. In the rear (*left* to *right*) are Orbital's Bruce Ferguson and Scott Webster and NASA's Jack Wild (Courtesy of Orbital ATK Corporation.)

shuttle over the next ten years, and would produce significant near-term cost savings for NASA. He outlined detailed provisions for minimizing the risks to NASA if Orbital could not deliver on its commitments. After a brief caucus, Wild and his associates told the Orbital team that NASA would indeed sign an agreement to allow it to proceed with TOS development on a commercial basis, and therefore that NASA would not fund the design or development of a similar capability.

It took more than two months to work out the specifics of the NASA–Orbital agreement, which was finally signed on April 18, 1983 (Fig. 9.2). A key paragraph read: "In consideration of the development of the TOS by OSC at no cost to the Government, NASA will not … initiate and directly fund the development of new alternative systems for TOS-class missions." Orbital would "have full responsibility for the development and fabrication" of the TOS; NASA would "monitor the technical aspects of the TOS development and operational programs" and "participate in design, test, and other reviews." In another key provision, the agreement noted that it did not obligate NASA "to purchase any amount of TOS hardware or related services from OSC." The agreement gave Orbital until September 15, 1983, less than five months in the future, to make "adequate arrangements for the funding of OSC's obligations." It gave NASA "the right to audit the costs of the TOS program" and to terminate the agreement "if OSC fails to meet its obligations … to the extent that the TOS development program or operational program has been substantially jeopardized."[9] NASA was being very careful in crafting the agreement with Orbital to protect itself against technical failure or unexpected cost increases.

The agreement did not involve the transfer of funds from NASA to Orbital or other subsidies, nor did it commit NASA to purchase one or more TOS for its use. Even so, it was unprecedented. Never before had NASA commited to depending on a privately funded supplier of a critical path system rather than fund the development of that system itself. *The New York Times* the next morning on the front page of its business section, in a story headlined "A Rocket's Private Financing," quoted Thompson as saying that the agreement "represents an important milestone in the development of a commercial space industry."[10]

With the signing of its agreement with NASA, Orbital could focus its energies on raising the money—the estimated need was $50 million by the end of 1983—to finance the initial stages of the TOS development program. Having the NASA agreement in place was critical to the success of the fundraising effort, as it gave investors a level of confidence that the government space agency saw Orbital's TOS program as viable, even though neither NASA nor any other customer had actually signed a contract to procure a TOS vehicle. Orbital also opened its first real office, near Tysons Corner in the Virginia suburb of Washington, DC. On the day before the first face-to-face meeting of the Orbital board, which at that point had as members Fred Alcorn, Tom Paine, and a New York investment banker, Douglas Luke, Thompson toured nearby furniture stores to find a conference table and six chairs for the meeting.

To find the investors needed to raise $50 million in the final months of 1983, the OSC team, now including several more employees, traveled to over 20 states and made over 100 presentations. According to Thompson, "we got it done … but just barely." In parellel with its

Fig. 9.3 An artist's concept of a transfer orbit stage and attached communication satellite being launched from the space shuttle. (Courtesy of Orbital ATK Corporation.)

fundraising efforts, Orbital was negotiating the TOS development contract with Martin Marietta. As 1984 began, the path to technical success with adequate financial backing was becoming clear.

There was, however, one problem. Orbital, by now renamed the Orbital Sciences Corporation, had no firm orders for a TOS. Thompson recognised that "commercial satellite owners and government spacecraft managers were still reluctant to commit the fates of their $100-million class payloads to an early launch on our unproven rocket." This situation persisted through most of 1985. Only toward the end of the year did Orbital get a tentative commitment from a communications satellite owner to purchase several TOS vehicles; it was also selected by NASA to provide a TOS for up to four science and application satellite missions (Fig. 9.3). Says Thompson, "as 1985 ended, our workforce of nearly 20 people celebrated these sales … Optimism remained high for all of four weeks."

Disaster, then Recovery

On the morning of January 28, 1986, *Challenger* blew apart 73 seconds after launch; its seven-person crew perished. The shuttle accident set in motion a searching White House review of the notion that the space shuttle was an operational vehicle that could be launched on a regular basis to carry various payloads into orbit. Thompson and his associates participated in the review, arguing that the shuttle should continue to be used for commercial and military launches. Their arguments did not prevail. On August 15, 1986, the White House announced that the shuttle would "no longer be in the business of launching private satellites."[11] Soon after, the Department of Defense began shifting most of its payloads from the shuttle to expendable launch vehicles.

These actions reduced the potential market for TOS by two-thirds. Fortunately for Orbital, NASA stuck by its commitment to purchase the TOS for future missions. One of those missions was Mars Observer, a planetary probe; NASA paid Orbital to modify the TOS so that it could be used as the upper stage of a Titan III expendable launch vehicle. NASA also contracted with Orbital for a TOS to take its advanced communications technology satellite (ACTS) into GTO after it was launched on the space shuttle. Mars Observer was launched in 1992, ACTS in 1993. Those two launches turned out to be the only uses of the TOS.

At the end of 1986, the two NASA contracts for TOS and several more potential orders for the transfer vehicle (which were never finalized) meant that Orbital could emerge from its post-*Challenger* survival crisis. Thompson, Ferguson, and Webster felt that "the company was back on its feet, if still somewhat shaken by the tremendous changes we had just lived through," and that Orbital had a "stable foundation for company growth and product line diversification in the years immediately ahead." A core objective of that diversification would be to reduce Orbital's dependence on NASA as its major customer.

Let's Build a Rocket![12]

In the aftermath of the White House decision to ban Shuttle use for launching commercial satellites, several of Orbital's early employees left the company. Nevertheless, they were replaced by other talented individuals who would be key to the next stage of Orbital's development, one in which the company would strive to diversify its activities and in the process end its dependence on NASA as its major partner. One of these new hires was Antonio Elias, described by one journalist as "the exuberant son of a Spanish diplomat."[13] Elias had been teaching at MIT before joining Orbital as its chief engineer on September 2, 1986. This was also the day that the company moved into its new offices in Fairfax, VA. A second key addition later in 1986 was Robert Lovell, a NASA manager who came to Orbital to pursue what he described as "the last big cookie – the one big thing left in satellite communications."[14] This "cookie"—defined as an opportunity for commercial success—was a satellite system to relay communications from many points to a single point, thereby allowing centralized monitoring of, for example, sensors along the Alaska pipeline or the location of railroad cars. It was Lovell's idea that was intended to be Orbital's second product line, a commercially developed network of small, relatively inexpensive satellites to serve as data relays. Orbital ultimately developed this system, designated ORBCOMM. However, before that development could be financially feasible, Orbital had first to figure out how to launch multiple satellites at an acceptable cost.

It fell to Elias to find a solution to the issue of affordable launch. An examination of opportunities for launching Orbital's small satellites as secondary payloads on emerging commercialized versions of the large pre-shuttle expendable launch vehicles found that most of the time the launches were not going to an appropriate orbit and that secondary payloads were at the mercy of the schedule for the primary payload. Neither of these conditions was acceptable. The next step for Elias was to survey the field to learn if there was under private-sector development a small rocket that could meet Orbital's needs. His survey did not turn up a viable option.

By spring 1987, it was becoming clear to Elias that "if somebody doesn't put together a low cost launch vehicle, then all these great things that we want to do won't happen." So, "it might as well be us." On April 7, 1987, while waiting for the start of a disorganized meeting convened by the Virginia Center for the Commercial Development of Space in a hotel near the Udvar-Hazy facility of the National Air and Space Museum, Elias somewhat idly drew an image of a small rocket launched from underneath an airplane. He remembered the 1985 Air Force test of an anti-satellite weapon (ASAT) launched by a rapidly climbing F-15 fighter, and wondered if something similar was possible for satellite launch. Elias showed his drawing to his two Orbital colleagues waiting for the meeting to start. They were intrigued by the idea and decided that they were wasting their time at the meeting, so they headed back to their Orbital office a few miles away. There they encountered Thompson and showed him the air-launch sketch. Thompson's first reaction was that the idea was somewhat "far-fetched"; he commented that "the battlefield of small launch vehicle programs is littered with the carcasses of failed start-ups." On reflection, however, he encouraged Elias and his colleagues to explore what he still thought was a "crazy idea."

Elias recognized that there were a number of advantages to launching a rocket from an airplane. The altitude and speed of the carrier airplane would lessen the performance requirements for the rocket, and launching above much of the atmosphere would reduce the dynamic pressures on the vehicle. He first approached the Air Force to see if it was possible to adapt its anti-satellite vehicle for space launch purposes. The service, stung by negative reactions to its ASAT test, told Elias to "go away." That meant that the new rocket would have to be designed from scratch.

One question was whether it was better to launch a larger rocket from a slower subsonic aircraft such as a Boeing 747 or a B-52, or a smaller rocket from a supersonic plane such as the Mach 3 SR-71 "Blackbird." Analysis by Elias and other Orbital engineers demonstrated that the subsonic option was preferable. The question, then, was how to inexpensively access a large airplane as part of the rocket development and test program. This is when NASA came into the act.

From 1959 to 1968, at its Dryden (now Armstrong) Flight Research Center in the California high desert NASA had used a B-52, originally designed as a strategic bomber, to launch the X-15 rocket plane. Although that B-52 had been mothballed after the X-15 program ended, it had recently been returned to service for some Air Force tests. Elias, Lovell, who by that point had been named manager of the new rocket project, and their colleague Bob Lindberg visited Dryden in fall 1987 to explore whether Orbital might be able to use NASA's B-52. "Much to our delight," Elias recollects, "Dryden's Director at that time, Marty Knutson, approved its use for our development flights at the end of that first meeting." Knutson made that decision without checking with his bosses at NASA's Ames Research Center or at NASA Headquarters in Washington. Moreover, Knutson agreed that NASA would charge only "out of pocket" expenses for the B-52 flights during the booster's test phase, and made land available at Dryden for Orbital to build an assembly and test facility for its proposed rocket. At that point the booster was designated only ALV, for air-launched vehicle. NASA's early willingness to support ALV development at little cost to Orbital was its key contribution to bringing the Pegasus launch vehicle into being, although, once Pegasus started flying, NASA also contracted for a number of launches of the rocket.

During 1987, work continued on the design of the launch vehicle without any public announcement of what Orbital was up to; according to Elias, the company was being "very coy" about its plans.[15] In September Orbital contacted several companies with respect to procuring solid rocket motors, still without revealing its intent to use them to power ALV. One of those companies, Hercules Aerospace Company, was so taken with the prospects of a new market for its rocket motors that it agreed, after Orbital revealed its plans, to be a 50/50 joint partner in developing the vehicle, sharing both development and production costs and potential profits. This was a fortuitous arrangement, since at the time Orbital was running short of the funds needed to finance ALV development.

A key design choice was to add delta-shaped wings to the vehicle; in the original concept there had been short, stubby, unswept, low-mounted wings. However, as design engineering proceeded, Elias decided that the wings should be delta shaped and mounted above the rocket body; this would best provide the lift needed in the very early stages of supersonic flight, seconds after the vehicle was dropped from its "first-stage" airplane and its rocket motor ignited. The rocket could begin its flight on a horizontal trajectory rather than almost immediately "swoop" to a vertical trajectory to avoid falling to Earth. After first considering contracting the wing's detailed design and manufacturing to a traditional airframe manufacturer that planned to build the wing from aluminum, Elias decided to assign that task to iconoclastic entrepreneur Burt Rutan, whom Elias described as "the wizard of carbon composites." In other unconventional design choices, Orbital decided to use in the rocket an inertial navigation system designed for a Navy torpedo and a computer developed for a railroad locomotive.

In anticipation of its new rocket being a success, in Spring 1988 Orbital also decided that it would need manufacturing capabilities for the booster. The experience of contracting out the engineering development and manufacturing of TOS had convinced Thompson and his associates that the company would be better off doing much of that work itself. Orbital set out to acquire Space Data Corporation, a small but rapidly growing Arizona-based builder of suborbital rockets and other space-related hardware. Even while the negotiations to merge the firms were going on, Orbital and Space Data managers made a joint presentation to the Defense Advanced Research Project Agency (DARPA) on why the combined firms were the best supplier for DARPA's "Standard Small Launch Vehicle" program; DARPA was an organization developing advanced military systems and with an ongoing interest in small satellites. On the basis of the joint presentation, DARPA awarded Orbital a contract for one launch, with options for five more. With this award, DARPA became the "anchor tenant" for the new rocket. The DARPA contract was finalized in July 1988, with the first launch scheduled for July 1989.

As they negotiated the agreement with DARPA, Elias and his team were now ready to unveil their plans to the aerospace community and general public. With the addition of the prominent delta wing, they had decided to call the vehicle "Pegasus" after the winged horse of Greek mythology. One description of Pegasus characterized it as "a 49-ft. torpedo with a delta wing." Orbital arranged with the trade journal *Aviation Week & Space Technology* for an "exclusive" in announcing the Pegasus program, and the cover of the journal's June 6, 1988 issue featured an artist's concept of the vehicle. In a lead article, the magazine called Pegasus "revolutionary" and suggested that it "could have a long-term effect on U.S. launch operations and help stimulate development of an entirely new class of small and medium-sized spacecraft." It characterized the Pegasus project as "one of the largest U.S. space commercialization efforts attempted to date" and noted that the vehicle was being "developed totally as a commercial venture." Pegasus was to be capable of launching a 600 pound payload into a 250 mile polar orbit and a 900 pound payload into a 250 mile equatorial orbit. The cost of Pegasus development was put at $40–45 million, and the projected price for a launch was set at $6–10 million, with a projection of 10–12 launches per year. One Hercules official was even quoted as suggesting that the market could reach one launch per week.[16]

The *Aviation Week* exclusive was scooped by a May 29 article in *The New York Times* that put a very different spin on the Pegasus project. Headlined "Military Plans a 3-Stage Rocket to be Launched from a B-52," the article, casting the project as being driven by security rather than commercial notivations, suggested that "the air-launched rocket system would be inexpensive, less vulnerable to attack than spaceports on the ground, and ideal for quickly lofting small spy satellites to monitor fast-moving battles." The *Times* article seemed intent on characterizing Pegasus in a negative light, suggesting that the prospective DARPA contract had "stirred concern on Capitol Hill because the rocket could be launched in secrecy" and "could be fired from remote parts of the globe, far from Soviet trawlers and spy satellites that monitor U.S. launches." Also, unnamed "Congressional experts" were worried "that the rocket could be used to launch anti-satellite weapons."[17]

The *Times* article did not succeed in putting a damper on Orbital's announcement of the project. As it announced Pegasus, it was putting a very positive public face on its status and outlook. Thompson told *Aviation Week* that by 1991, three years away, the company expected to have revenues of $150 million, half from TOS and half from Pegasus. Although there were still only two TOS under contract, there was a continuing hope both that more of the transfer stages would be sold and that Pegasus would find a ready market. One investment banker noted that "the financial community respects the young managers" who started the company, suggesting that "they did what President Reagan asked private investors to do for commercial space, taking the burden off the government's back."[18] This positive assessment by the investment community was important to Orbital, since the company was planning an initial public offering of its stock in the next year or so. To be listed on the New York Stock Exchange, a firm had to have at least $100 million in annual revenues and to show an annual profit. Thompson, Ferguson, and Webster were optimistic that Orbital would soon meet these requirements, and they needed an infusion of additional cash to support their plans for the future. With the acquisition of Space Data in 1988 and success in winning several nonspace contracts from the Department of Defense, at the end of 1989 OSC had 475 employees and $80 million in revenues, with good prospects for future growth.[19]

Pegasus' First Flight—and Another Orbital "Survival Crisis"

On August 10, 1989, Orbital rolled out a Pegasus prototype (Fig. 9.4), loaded with inert rubber rather than actual propellant. The roll-out at NASA Dryden was a time of high optimism and was "complete with VIPs, TV coverage, refreshments and a marching band." Orbital hoped

Fig. 9.4 A prototype of Pegasus is put on display at NASA's Dryden Flight Research Center on August 10, 1989. The vehicle carried both the logos of its anchor tenant, DARPA, and NASA, even though NASA had not yet contracted for a Pegasus launch. (Courtesy of Orbital ATK Corporation.)

to carry out two launches in 1989, the first scheduled for November, and four or five launches in 1990. Elias was quoted in October 1989 as saying that with Pegasus and its planned small ORBCOMM satellites, OSC wanted "to be the Apple of space."[20]

That first launch was delayed for six months, however. Several problems arose during "captive carry" tests of the Pegasus booster mounted under the right wing of the NASA B-52, and both Orbital and DARPA wanted a fully successful captive flight before attempting the first launch. After the third captive carry flight was successful in January 1990, the date for that launch was set for February 28. There were a few more final delays as Orbital made sure that Pegasus was ready for its first flight; the launch was finally scheduled for April 4, 1990.

As the first launch of Pegasus was planned, then slipped, Orbital was planning another launch: it was preparing for an initial public offering of the company's stock. Despite the best efforts of Thompson and his associates to maintain some separation between the Pegasus launch date and the date of the initial public stock offering, the two seemed somehow "quantum linked."[21] Orbital's hope was to have a successful first flight in February before its stock went public in late March, but this proved impossible. With the latest slip, the first launch of Pegasus was to take place two weeks after March 23, the date scheduled some time earlier for the stock offering.

However, an unexpected article that appeared on the front page of the *Wall Street Journal* on the morning of the planned stock offering threw a monkey wrench into Orbital's plans. The story carried the headlines "Space Gamble" and "Big Risks." It described the Orbital founders as "three Harvard 'Space Nuts,'" suggesting that they were "fools," "visionaries," or a "mixture of both." It anticipated a successful Pegasus launch, but quickly added "then again, the rocket could just blow up." The article quoted Thompson as suggesting "subconsciously, I'm worried we're not really ready to go." The article also quoted Bruce Ferguson as saying that Orbital had engaged in "marketing puffery" by saying in 1988 that the company was already profitable, when in fact it had posted a loss for the year.[22]

The article communicated an impression of Orbital's chances of Pegasus success that the company could hardly welcome on the day of its stock sale, and, after hurried consultations with the investment firm underwriting the offering and indications that several investors intending to purchase Orbital stock were having second thoughts, Thompson and his associates decided to withdraw the offering until conditions were more propitious. That withdrawal put the fate of the offering, and indeed of the company, squarely on a successful Pegasus first launch. Reporting the postponement of the offering, the *Wall Street Journal* commented that scheduling the launch so close in time to the offering had been necessary "to satisfy long time investors" in Orbital. The paper also noted that Orbital had a deadline of April 30 to satisfy the conditions its creditor banks had placed on its revolving bank loans; this added further pressure to achieving a successful launch. The trade weekly *Space News* reported that "several Wall Street analysts … said the decision to withdraw the stock made the company's ability to raise money on Wall

Street for the foreseeable future completely contingent on a successful first launch of Pegasus."[23]

The morning of April 4 was rainy, and the Pegasus launch team decided to wait another day before attempting the launch. On April 5, 1990, just two days short of three years since Elias had first imagined Pegasus, the B-52 carrying the rocket took off just after 11:00 Pacific Daylight Time, and at 12:10, with the B-52 43,000 feet above the Pacific Ocean, Pegasus was dropped, its first stage ignited, and it accelerated to a 320 nautical mile polar orbit. Elias later reported it was "a perfect countdown and a perfect launch." After the success, "everybody was dancing and shouting for joy." The Pegasus carried two payloads, a small DARPA relay satellite and a larger NASA satellite called Pegsat that had been constructed in less than a year to take advantage of excess payload capability on the first launch. Although DARPA had paid for the launch, NASA's Pegsat was identified as the primary payload.

After the launch, Thompson was quoted as saying: "Pegasus is a product of outstanding teamwork between the U.S. Government and the private sector, and serves as a model for government–business cooperation in the advancement of space technologies." *The Washington Times* editorialized:

> The significance of Pegasus is that the government didn't do it; a group of good old-fashioned American entrepreneurs did. Every one of the 60 million dollars that went into the rocket's development came out of the wallets of risk-taking businessmen. If Sputnik was to the conquest of space what the Nina, Pinta, and Santa Maria were to the discovery of the New World, Pegasus is like the first small but privately owned tobacco farm outside Jamestown.[24]

With the launch success, and after a quick round of consultations with potential investors, Orbital scheduled its stock offering for April 24. Its investment advisors priced the stock at $14 a share, a dollar more than had been the planned price a month earlier; this was the bonus from Pegasus' success. Of the 2.4 million shares on offer, half were bought by the day's end. One investor commented that "these are the type of guys I like to give a chance to. They're innovative and they've created a whole new market, making space cheap and affordable for the commercial user."[25] With its stock offering, Orbital became the first entrepreneurial space company to "go public."

Fig. 9.5 A Pegasus booster seconds after being released from its B-52 carrier aircraft. (Courtesy of Orbital ATK Corporation.)

The second launch of Pegasus did not occur until July 1991; due to a first-stage problem, it carried seven small DARPA satellites into an incorrect, but still usable, orbit (Fig. 9.5). The next Pegasus launch, with a Brazilian payload, was not until 1993. In 1990, NASA signed an agreement with Orbital formalizing the terms for access to NASA facilities, including the Dryden B-52, for use by Pegasus. In announcing the agreement, NASA noted that it was "committed to facilitating and encouraging the commercial use of space by U.S. firms."[26] In 1991, NASA issued a request for proposal for a small satellite launch services contract. That request set weight-lifting requirements some 10% above Pegasus' capability; Elias suggests that this was not an anti-Pegasus action on NASA's part, but rather NASA's use of an outdated version of Pegasus' performance capability.[27] This NASA requirement led Orbital to design a Pegasus, designated

Pegasus XL, with additional weight-lifting capability. Orbital's bid on the NASA contract was successful. Since the mid-1990s 22 NASA missions have been launched on Pegasus XL boosters. From 1995, Pegasus was also used to launch Air Force payloads and Orbital's ORCOMM satellites; that latter role was the original mission that led to the booster's development. The most recent Pegasus launch was a NASA Earth science satellite in December 2016. In total, Pegasus over its quarter-century of operation has placed over 80 satellites into orbit.

Lessons Learned

Almost two years before the first launch of Pegasus, a June 1988 news article in the *Houston Post* was headlined "Young Firm Bet on NASA and Won." The article added "Orbital Sciences and its 70 employees [this was before the acquisition of Space Data] would be nowhere without NASA, source of the company's entire revenue last year."[28]

This was an accurate description of the situation in mid-1988, but it was a situation that Orbital's founders, David Thompson, Scott Webster, and Bruce Ferguson, were by that time trying hard to escape. The Orbital–NASA partnership was not "a marriage made in heaven." As Orbital emerged from the traumatic post-*Challenger* transition in national space policy, Thompson recognized that its "original business model had several major shortcomings":

> First, the company was almost completely dependent on NASA's Space Shuttle which was revealed by the *Challenger* disaster to be less reliable and serviceable than previously believed; second, we lacked effective control over production costs and schedules, due to outsourcing nearly all engineering and manufacturing work to larger aerospace contractors; and finally, and perhaps most critically, despite scaling back our early ambitions for a reusable OTV [orbital transfer vehicle], our TOS project was still a relatively large, slow and expensive venture which was inherently mismatched to the advantages of a small, agile and cost conscious enterprise … We knew these drawbacks had to be addressed for the company to accomplish the things we imagined it doing in the future.[29]

When they founded Orbital in 1982, Thompson, Webster, and Ferguson had had unrealistically high ambitions: that they could finance and manage the development of a powerful Centaur upper stage for NASA's space shuttle, and that they could convince NASA to step aside, not developing this needed capability as a government-funded program but rather taking the risk of allowing three unproven entrepreneurs to spearhead that development. This was an audacious proposition, and while NASA and Congress did not accept it, NASA was willing to accept an alternative proposal, substituting a smaller upper stage, TOS, for Centaur, and agreeing not to develop under NASA control a comparable capability. NASA's willingness to take a risk on an unproven entrepreneurial organization that in 1983 consisted of little more than the vision, enthusiasm, and apparent competence of its three young founders, with minimal financial backing, was the result of a convergence of several factors. Certainly the emphasis of the Reagan White House on commercializing space provided an influential political and policy context for the NASA decision to work with Orbital. The support of key NASA leaders, from Administrator Beggs, Associate Deputy Administrator Culbertson, and Associate Administrator Abrahamson, allowed lower-level NASA staff, such as Jack Wild, to take a chance on Orbital. The anticipation that the space shuttle would soon be flying regularly, with many of its missions carrying commercial communications satellites, influenced everyone involved. The fact that the capability offered by TOS would make the shuttle competitive with the European Ariane launcher in the global space market made the Orbital initiative politically attractive to those concerned about continuing US space leadership.

While it was the TOS program that Thompson characterized as "large, slow and expensive" and "inherently mismatched" to a "small, agile and cost-conscious enterprise," implicit in his observation were the downsides of partnering with NASA itself. Particularly as it tried to respond to the pressures from the Reagan White House to give much more emphasis to space commercialization, in the first half of the 1980s, NASA was caught between its way of doing things that had been set in place during the Apollo program—fast paced but large scale and not particularly cost conscious—and administration demands for commercial-like cost consciousness and flexibility. This made the space agency a less than perfect partner for a small company as it tried to establish a stable basis for its future. One lesson of the NASA–Orbital partnership on TOS is that a mismatch between the organizational attributes of two partners is a barrier to full success. Having dealt with NASA for several years, by 1987 Orbital was eager to end its dependence on a partnership with the space agency and strike out in a new direction. Orbital certainly wanted to retain NASA as a potential customer for its products, but also wanted freedom from the strictures of working in partnership with NASA in most of its future ventures.

In its two original ventures, TOS and Pegasus, Orbital was over-optimistic in its projection of potential markets. Perhaps this is a tendency endemic to the entrepreneurial space sector—or perhaps to all entrepreneurial ventures. And perhaps it is a necessary element in technological progress. Antonio Elias at one point described Orbital's ambition as to become "the Apple of space." This was at a very early stage in Apple's development; it is doubtful that Elias anticipated Apple's success in becoming one of the world's most valuable companies. Rather, Elias was reacting to Apple's success in challenging the dominance of large companies in the computing field. Similarly, the optimism of the small cadre of early Orbital leaders and staff regarding the company's future prospects was likely an essential element of the its growth into a major player in aerospace. The lesson here is that unrealistic early expectations may be essential for eventual entrepreneurial success; not all entrepreneurial ventures fail. Also, without the willingness of established organizations, in this case NASA, to discount unrealistic projections and recognize and encourage the strengths of an aspiring entrant, the path to technological innovation and business success would be much steeper.

This account of the NASA–Orbital relationship demonstrates the variety of ways in which NASA has been able to stimulate innovation in the entrepreneurial space sector. It was a NASA-funded study at the Harvard Business School that first brought Orbital's founders together. The field research associated with that study gave the three and their study partners direct familiarity with the established public and private space sector, allowing them to plan their space business venture on an informed basis. When the three young men first approached NASA with an overly ambitious proposition to take responsibility for developing a complex and critical space system, they were "let down gently." Instead of shutting its door on them, NASA encouraged them to continue their search for an alternative first product. When Orbital came back with that alternative, the TOS, after due diligence NASA took the significant risk of agreeing to depend on Orbital to deliver a system important to economic success of the space shuttle. After the *Challenger* accident and the decision to remove the shuttle from the commercial launch market, NASA honored its commitment as a customer for TOS, providing the cash flow that

Orbital needed to survive. And when Orbital needed NASA's support to test its second product, an air-launched rocket booster, there was no hesitation on the part of a mid-level NASA official to provide that essential support.

In a sense, Orbital Sciences Corporation has reached its current status as a major aerospace company in spite of its early projects, not because of them. While TOS did not provide the hoped-for early economic returns and while the payoffs from Pegasus took longer to arrive and came in ways not originally anticipated, they did demonstrate that the three founders, and the small team of high-quality engineers and managers they assembled, could actually succeed in pulling off technologically challenging projects. As Orbital's early investor Fred Alcorn suggested: "these three guys, they're going to start out with the TOS, but I really feel they'll go on to something greater."[30] With their accomplishments and varying awards over the first decade of the company's existence, Orbital's leaders validated Alcorn's forecast. As David Thompson said at a press conference after the first launch of Pegasus, but with applicability to more than just Pegasus: "We said we'd do it … and now we had done it!" By 1990, Orbital was on a trajectory to success that was no longer dependent on NASA's support. Yet without that early support, Thompson would not have been able to make his boast.

Notes

1. David W. Thompson, "The Early Years," in Orbital Sciences Corporation, *An Adventure Begins: Orbitals' First 25 Years* (Dulles, VA: Orbital Sciences Corporation, 2007), 18. This chapter was greatly facilitated by the existence of this corporate history, and by the willingness of David Thompson and Antonio Elias to share their memories of Orbital's evolution in September 21, 2015 interviews with the author. Thompson also provided comments on an early draft of the chapter and made reports, pictures, and images from Orbital's archives available for use in this study. In fact, Pegasus was not "the world's first privately developed launch vehicle." Space Services Incorporated, based in Houston, TX, successfully launched its Conestoga I booster on September 9, 1982. The rocket deployed a dummy payload at an altitude of 331 kilometers, but the payload did not go into orbit, and there were no subsequent launches of that Conestoga I design. In contrast, Pegasus did carry its payloads to orbit, and by the time of the presidential award Orbital had orders for 30 Pegasus launches.

2. Ibid., 8.
3. Andrew J. Butrica, *Single Stage to Orbit: Politics, Space Technology, and the Quest for Reusable Rocketry* (Baltimore: The Johns Hopkins University Press, 2003), 7.
4. Unless otherwise noted, this account of the first few years of Orbital's history, including quoted material, is drawn from David Thompson's essay "The Early Years" in *An Adventure Begins* and an interview with David W. Thompson, September 21, 2015.
5. John M. Logsdon et al., eds., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program*, Volume I: Organizing for Exploration, NASA SP-4407 (Washington, DC: Government Printing Office, 1995), 591.
6. The following paragraphs are drawn from Orbital Systems Corporation, "Presentation to NASA Headquarters," December 9, 1982. (Copy of presentation courtesy of David W. Thompson.)
7. NASA Press Release 82-189, "NASA and Orbital Systems Corporation Sign Agreement," December 17, 1982, Folder 10778, NASA Historical Reference Collection, NASA Headquarters, Washington, DC. (NHRC)
8. Jerry Laws, "Young Firm Bet on NASA and Won," *Houston Post*, June 19, 1988, 19, Folder 10776, NHRC.
9. "Agreement for the Commercial Development and Operational Use of the Transfer Orbit Stage between the National Aeronautics and Space Administration and Orbitals Systems Corporation," April 18, 1983. (Copy of agreement provided by David W. Thompson.)
10. John Noble Wilford, "A Rocket's Private Financing," *The New York Times*, April 19, 1983, D1, D21; NASA could not by law offer Orbital the exclusive right to develop the TOS on a commercial basis, and thus offered through a notice in *Commerce Business Daily* the same arrangement as had been concluded with Orbital to other aerospace firms such as Boeing and McDonnell Douglas. Neither company pursued such an agreement.
11. President Ronald Reagan, Statement by the President," August 15, 1986, reprinted in John M. Logsdon et al., eds., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program*, Volume IV, Accessing Space, NASA SP-4407 (Washington, DC: Government Printing Office, 1999).
12. Unless otherwise noted, this account is drawn from Antonio Elias, "The Pegasus Rocket: We Said We'd Do It … and We Did It! (1987–1990)" in *An Adventure Begins* and an interview with Antonio Elias, September 21, 2015.
13. Bob David, "Space Gamble: Start-Up Firm Faces Big Risks in Launching Rocket from a Plane," *Wall Street Journal*, March 23, 1990, 1.

14. *An Adventure Begins*, 34.
15. Interview with Antonio Elias.
16. Craig Couvalt, "Commercial Winged Booster to Launch Satellites from B-52," *Aviation Week & Space Technology*, June 6, 1988, 14–15. The forecast of one launch per week is in a follow-up story by John Stodden, "Orbital Sciences Charts Rapid Growth with Reduced Risk for Pegasus Investment," *Aviation Week & Space Technology*, June 27, 1988, 51.
17. William Broad, "Military Plans 3-Stage Rocket to be Launched from a B-52," *The New York Times,* May 29, 1988,
18. Stodden, "Orbital Sciences Charts Rapid Growth," 52–53.
19. "Orbital Sciences Corporation—Company Profile,"
20. Bruce A. Smith, "Pegasus Air-Launched Test Vehicle is Rolled Out," *Aviation Week & Space Technology*, August 14, 1989, 36. Sandra Sugawara, "OSC, a Successful Company Still Trying to Get Off the Ground," *The Washington Post*, October 23, 1989, Folder 10776, NHRC.
21. Interview with David Thompson.
22. Robert Davis, "Space Gamble: Start-Up Firm Faces Big Risks in Launching Rocket from a Plane," *Wall Street Journal*, March 23, 1990, 1.
23. Robert Davis, "Orbital Sciences Postpones Offering, Citing News Article," *Wall Street Journal*, March 26, 1990, 1. Lon Rains, "Investors Wait as Pegasus Nears First Flight," *Space News*, April 2–8, 1990, 1.
24. Orbital Sciences Corporation News Release, "First Pegasus Launched Successfully; Commercially-Developed Rocket Places Satellite in Orbit," undated but April 5, 1990, Folder 10778, NHRC. "On a Wing and $60 Million," *Washington Times*, April 30, 1990, Folder 10778, NHRC.
25. Laura Litvan, "Orbital Holds Own as Stock is Offered to Public," *The Washington Times,* April 25, 1990, Folder10778, NHRC and Willie Schatz, "Orbital 'Go' for Launch of Shares," *The Washington Post*, April 24, 1990, Folder 1990, NHRC.
26. NASA News Release 90–92, "NASA, Orbital Sciences Corporation Sign Agreement," July 3, 1990, Folder 10778, NHRC.
27. Interview with Antonio Elias.
28. Jerry Laws, "Young Firm Bet on NASA and Won," *Houston Post,* June 19, 1988, Folder 10776, NHRC.
29. Thompson, "The Early Years," *An Adventure Begins*, 14.
30. Laws, *Houston Post.*

CHAPTER 10

The Discovery Program: Competition, Innovation, and Risk in Planetary Exploration

Michael J. Neufeld

When Congress approved NASA's Discovery program in 1993, the action a milestone in the agency's search for lower-cost, innovative, robotic space science missions. The competitive selection of spacecraft proposals led by principal investigators (PIs) inverted the relationship between NASA centers and mission scientists. In the old model, a flight mission or series was assigned to an agency center, which would pick the instruments to hang on the spacecraft. Science often took a back seat to engineering. In the Discovery model, the winning PI would be completely responsible for delivering the science and the successful mission under a cost cap defined in the program. Rather than each mission being funded individually, which was often politically difficult, there would be a dedicated line in NASA's budget. Innovative and risky management approaches, including management by non-NASA organizations and streamlined systems engineering procedures, were

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favored. Discovery became the marquee project of Administrator Daniel Goldin's "faster, better, cheaper" approach.[1]

However, after the failures of two Mars spacecraft in 1999, Goldin and NASA became significantly more risk averse. That affected Discovery, whose own crisis began later, in mid-2002, with the failure of CONTOUR (Comet Nucleus Tour), followed by budget and schedule calamities affecting several spacecraft in development. The competitive selection process had favored the most science that could be crammed under the cost cap, leading to more technically complex spacecraft than originally expected. Mission selections slowed drastically due to the resulting cost overruns, exacerbated by raids on Discovery's budget to prop up other NASA projects, and by longer-lasting operations costs for the ambitious missions, once launched. In order to reduce the risk of failure, the agency raised budget reserve and review requirements for new proposals, further increasing cost and making flights less frequent. With "better, faster, cheaper" methods discarded and cost caps raised, Discovery could no longer be called a low-cost program. Yet the central innovation of PI-led competitions has delivered many spectacular successes in solar system exploration on a relatively lean budget, and has inspired the reform or creation of other programs on the competitive model (like Explorer, New Frontiers, and Mars Scout). It demonstrates that competition can work to reduce cost and increase innovation at NASA, but also that cost savings will suffer if the agency becomes too risk averse.

Program Origins, 1989–1993

Discovery grew out of a perceived crisis in NASA's planetary exploration program. In the 1980s, overruns and delays in the only new projects—Galileo (a Jupiter orbiter and atmospheric probe), Magellan (a Venus radar mapper), and Mars Observer (an orbital mission)—were made even worse by the *Challenger* shuttle disaster of January 1986. No NASA planetary mission was launched between 1978 and 1989. What new data there was came from spacecraft launched in the 1970s, notably Voyager and its flybys of the outer planets. Large and expensive "flagship" missions like Galileo and Magellan cost hundreds of millions or billions of dollars, resulting in few opportunities to fly experiments. An attempt to start a low-cost mission line for the inner solar system based on a commercial Earth-orbiting design, Planetary Observer, got into deep trouble as Mars Observer faltered. It proved far from simple to modify the original design; scientists also tried to pile in as much instrumentation as they could, given that it was the only Mars mission for years. After the shuttle disaster, Lennard Fisk, Associate Administrator of the Office of Space Science and Applications (OSSA), decided to postpone Mars Observer two years to the next launch opportunity in 1992, and change it to an expendable booster. Nevertheless, he had to accept the consequence: another big cost increase.[2]

By 1989, disgruntlement in the planetary science community led Geoffrey Briggs, then head of OSSA's Solar System Exploration Division, to initiate discussions of a new low-cost program, one that might give mission leadership to university scientists. However, he ran into the entrenched interest of NASA's only planetary spacecraft center, the Caltech-operated Jet Propulsion Laboratory (JPL) in Pasadena, CA, and community skepticism because of the souring of Planetary Observer. That program seemed likely to end with only one mission (as was indeed the case—and it failed). At a strategic planning workshop for OSSA in summer 1989, Stamatios M. "Tom" Krimigis of Johns Hopkins University's Applied Physics Laboratory (APL) made a key intervention. He argued that a much better model would be the Explorer Program of small Earth-orbiting spacecraft, which served the space physics community out of which he came, as well as space astronomy. He used as an example the Advanced Composition Explorer (ACE) that APL was then designing. The argument sufficiently impressed Briggs that he began an initial study of what he called the Discovery program, which would emulate the Explorer model of a permanent budget line, rather than a separate appropriation for each "new start." He appointed an entrepreneurial mission designer and scientist, Robert Farquhar, then working at the Goddard Space Flight Center, to head it on a part-time basis and created a science working group to examine potential missions. A rendezvous with a near-Earth asteroid was already in discussion as a possible objective, given growing scientific interest in the small bodies of the solar system and the relatively low energy requirement for such a mission.[3]

However, Discovery made little progress over the next year, and Fisk replaced Briggs with Wesley Huntress, a distinguished former JPL astrochemist, as head of solar system exploration. Huntress saw Discovery as a critical program for reforming his unit. In his view, JPL had demonstrated its skills in outstanding flagship programs like Viking and Voyager, but was complacent and entrenched in a way of doing business that favored giant, expensive spacecraft; it needed competition. Looking around, he saw APL and the Naval Research Laboratory as the institutions immediately at hand that could build small planetary spacecraft, but the latter was not interested in getting into NASA's game. Huntress gave study contracts for Near-Earth Asteroid Rendezvous (NEAR) to APL and JPL, leading to a "shoot-out" in Pasadena in May 1991. The result was embarrassing for JPL. Its first proposal said that it needed nearly $450 million for a three-spacecraft program to get a full mission to an asteroid. In contrast, APL's team said it could be done for $110 million and one spacecraft, a figure that invited skepticism as being too low. In fact, JPL's proposal was so badly received that its director asked for a second chance. After a month, a group led by Tony Spear, a known JPL maverick who had rescued Magellan from failures in Venus orbit, came back with a single spacecraft for $150 million. This was respectable, but to Huntress it was no contest, and he gave the win to APL.[4]

In fall and winter 1991–1992, Huntress's and APL's assumption that NEAR would be first was upset, however, by internal NASA politics. Michael Griffin (later NASA Administrator) had been brought into head an Exploration directorate to revive President George H. W. Bush's ill-fated Space Exploration Initiative (SEI) of 1989 for human flights to the Moon and Mars. Administrator Richard Truly gave Griffin a small lunar mission that Huntress had started in place of Lunar Observer. Afraid OSSA would lose Mars too, Richard Truly took a small lander project that had been studied at NASA Ames Research Center and gave it to Tony Spear at JPL, and combined it with a separate proposal for a microrover to be carried by the lander. That project would become Mars Pathfinder. Tom Krimigis, APL Space Department head, was unpleasantly surprised by the news in March 1992 that NEAR was now bumped to second place in Discovery, with no launch projected before 1997.[5]

Huntress and Fisk made these decisions in the context of much agency turmoil. The era of expanding NASA budgets under Presidents Reagan and Bush came to a sudden halt in 1991 due to foreign and domestic crises, the end of the Cold War, and NASA embarrassments, above all huge SEI budget estimates and the flawed Hubble Telescope mirror discovered in mid-1990. OSSA had to eliminate a couple of flagship missions and find budget reductions in others. The Bush Administration, frustrated with what it saw as NASA's costly, sluggish, and bureaucratic methods, and impressed with the Strategic Defense Initiative's faster and riskier approach, dumped Truly and brought in

Daniel Goldin as Administrator in April 1992. He was a veteran of secret military and intelligence space programs at contractor TRW and came with an agenda of forcing through "faster, better, cheaper" methods of spacecraft development. By fall 1992, Goldin had decided to get rid of Fisk and install Huntress as Associate Administrator, in significant part because Goldin had discovered the latter's Discovery program. However, Fisk's removal was put on hold by the presidential election and the inauguration of Bill Clinton. In 1993, Goldin was confirmed, Fisk quit, and Huntress was installed as head of the Office of Space Science (OSS; Applications became a separate office).[6]

Because of the 1992 cuts, Discovery's first appropriation had been pushed back another budget year, but thanks to study contracts given in the spring, APL's NEAR and JPL's Mars Pathfinder had advanced. Krimigis was determined not to accept second place without a fight. He had hired Bob Farquhar from NASA and set him to work on finding a more interesting asteroid than the minor body that was to be the targeted for a rendezvous in 1998. Farquhar, a genius with trajectory design, found that if NEAR was launched in early 1996, it could reach the important Earth-crosser 433 Eros. That would have the side benefit of beating Pathfinder to the launch pad. Yet President Clinton's first budget submission in spring 1993 had no money for NEAR, which was to begin a year later. That set up a fight. Krimigis was very experienced in Washington power games and possessed outstanding connections to Maryland's congressional delegation, above all Senator Barbara Mikulski. He orchestrated a lobbying campaign by scientists friendly to NEAR and induced Mikulski's office to question the appropriateness of Pathfinder, a technology demonstrator, to what was supposed to be a science program. Goldin, who only cared about the Mars mission, was furious about this intervention, but Huntress was very happy when Mikulski engineered a compromise in fall 1993 that funded both to the tune of $132 million. Discovery had started much better funded than Huntress had any right to expect.[7]

Discovery in the Heyday of "Faster, Better, Cheaper," 1993–2001

The program began with two predetermined missions without PIs, but Huntress' intent was always to implement the full model once Congress and the President had approved the program. That involved a competitive selection of PI proposals, with science as the primary driver for selection, followed by technical merit. Primary conditions were a mission cost cap of $150 million in 1992 dollars, not including the launch vehicle, and a mission development time of no longer than 36 months. The launcher could be no bigger than a medium-sized Delta II. The expectation was that there would be a Discovery launch every 18 or 24 months, if the President and Congress funded the program as a "level of effort" budget line of $85 million a year, with $10 million for advanced technology and instrument development and the remainder for missions. Dan Goldin was happy to use Discovery as a marquee program in his campaign to shake up NASA's bureaucracy and spacecraft development processes. Nevertheless, it would take until the FY 1996 budget (which began in late 1995) before Congress actually was impressed enough by the program's progress to legislate the standing budget line.[8]

Even before program approval in fall 1993, NASA had held a workshop at San Juan Capistrano, CA, in November 1992 to prepare for future competitions. Concepts for small planetary missions were offered by 73 teams from universities, laboratories, corporations, and NASA centers. The results were encouraging—there were many imaginative ideas that might fit under the cap. OSS selected 11 of the best for further development funding, preparatory to launching the first Announcement of Opportunity (AO) competition in 1994.[9]

A follow-up management workshop was held in April at the same location. Two dozen space science insiders discussed how the PI-led model could actually be implemented. Among the key conclusions were that Discovery, which they enthusiastically endorsed, should aim for one selection and one launch a year, and not be run out of NASA Headquarters, but rather have a program office to provide "contract management and technical 'oversight.'" Regarding leadership they stated: "most PI's do not wish to be 'Project Manager' of their mission," "a few … do not wish to team with a NASA Center," "most PI's will favor roles as mission architect and science leader," and "most universities have *neither the will nor the means* to accept sole responsibility for an entire mission." These conclusions addressed two key questions about the PI model: (1) were scientists, mostly university based, capable of running a $150 million mission; and (2) how were they to deal with the technical and administrative complexity of developing a spacecraft and project while adhering to federal laws and requirements? Failure was certainly a possibility, and the workshop report stated that NASA had to "be prepared to *cancel* any non-performing missions, in any Phase, from A [detailed study] to C/D [full development and production]."[10] The report hit upon some of the other key questions as Discovery developed: if the traditional model for solar system exploration was thrown out (where a NASA center, almost exclusively JPL, was assigned a mission, then held a competition for the instrument selection or perhaps a spacecraft production contract), what role would the agency play in the new program? Only oversight? Would NASA centers be central or marginal? Would risk be tolerated and would projects actually be canceled? And would missions really be launched every year or two? Certainly, in the heyday of Goldin's "faster, better, cheaper," risk and speed were at the heart of NASA's rhetoric and were strongly supported by Wes Huntress in OSS.

In 1994, as scheduled, OSS released the first Discovery AO, and at the end of February 1995 Huntress chose the first new mission, Lunar Prospector, as well as three proposals for Phase A competition. Later in 1995, Stardust, which was to return samples of dust from a comet (Fig. 10.1), won over a Venus mission and one to sample solar wind particles. Two years later the latter was selected under a new name, Genesis.[11]

Lunar Prospector was an exception in Discovery history, and not only in its selection without further competition. It had originated as a private mission to prospect for Moon minerals, then the NASA Office of Exploration began funding it in 1991. Thus it had development history and prototype hardware. With Goldin's elimination of Exploration in 1994, it went searching for a home. Led by PI Alan Binder, who later exited Lockheed Martin to form his own private Lunar Science Institute, it began essentially as a Lockheed mission with minimal NASA involvement. However, the agency wanted to exercise project management, so it gave oversight to Scott Hubbard at the Ames Research Center, causing friction with Binder. The early 1998 launch on Lockheed's Athena II rocket, with a heritage of intercontinental ballistic missile solid-fuel stages, cost little (although delayed by problems) because of a special promotional price from the company. The entire project cost about $63 million, an extraordinarily low price even for a lunar mission, in significant part because there was no new technology development and a fairly basic instrument package designed to map surface elemental abundances. Its scientific result would have been unimpressive if it had not provided further evidence of possible water ice at the lunar poles, but it was cheap

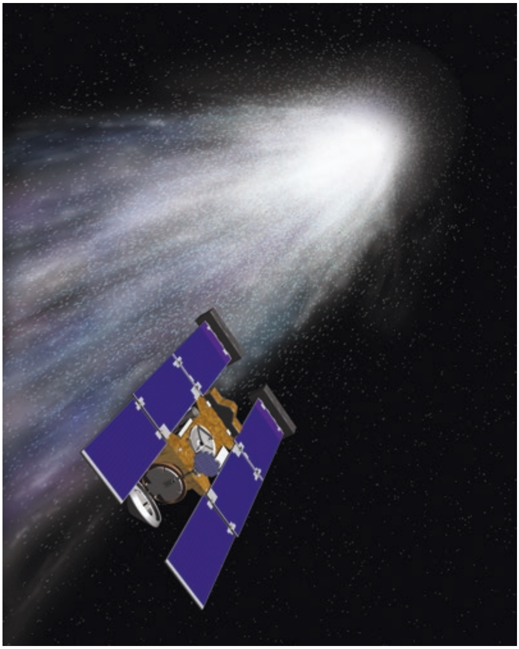

Fig. 10.1 This artist's rendering of the Stardust spacecraft shows it encountering Comet Wild 2. The spacecraft was launched on February 7, 1999, from Cape Canaveral Air Station, FL, aboard a Delta II rocket. It delivered samples from the comet to Earth in January 2006. (NASA/JPL, image number PIA03183, public domain) (Available at https://images.nasa.gov/#/details-PIA03183.html.)

and fast, as Goldin wanted. Other than APL's NEAR mission, which came in at a little over $100 million up to thirty days past launch, it was the only Discovery project that was much below the cost cap.[12]

The history and patterns of Discovery mission selections can be seen in Table 10.1. It is striking that all but two were chosen in 2001 and earlier, not counting the selection currently in process. (The Science Mission Directorate or SMD, the new name of OSS since 2003, has announced will probably pick two in 2016).[13] The sustainability of a selection every other year and launches on a similar pace required occasional missions like Lunar Prospector that were very cheap, relatively quick, and short-lived. Once Discovery drifted into the selection of more exciting, scientifically valuable programs up against the cost cap, with longer development times and even longer operational lives, an AO every other year would become unsustainable.[14]

Also notable is the greater diversity in the 1990s in the lead centers managing these projects. Johns Hopkins APL had three out of the first eight, and Ames one. Since Deep Impact in 1999, every mission has

Table 10.1 Discovery Missions

Name	*Selection*	*Launch*	*Principal Investigator/ Institution*	*Lead Center*	*Subcontracting Manufacturer*	*Target*
Mars Pathfinder	1992	1996	None/JPL (M. Golumbek, PS)	JPL	JPL	Mars
NEAR	1992	1996	None/APL (A. Cheng, PS)	APL	APL	Mathilde, Eros
Lunar Prospector	1995	1998	A. Binder/Lunar Science Institute	Ames	LM Sunnyvale	Moon
Stardust	1995	1999	D. Brownlee/ University of Washington	JPL	LM Denver	Comet Wild 2
Genesis	1997	2001	D. Burnett/ Caltech	JPL	LM Denver	Solar wind/ Earth–Sun L1
CONTOUR	1997	2002	J. Veverka/ Cornell	APL	APL	2 comets (failed)
MESSENGER	1999	2004	S. Solomon/CIW	APL	APL	Mercury
Deep Impact	1999	2005	M. A’Hearn/ University of Maryland	JPL	Ball Aerospace	Comet Tempel 1
Dawn	2001	2007	C. Russell/UCLA	JPL	Orbital Sciences	Vesta, Ceres
Kepler	2001	2009	W. Borucki/Ames	JPL/ Ames	Ball Aerospace	Extrasolar planets
GRAIL	2007	2011	M. Zuber/MIT	JPL	LM Denver	Moon
InSight	2012	2018*	W. B. Banerdt/JPL	JPL	LM Denver	Mars
Lucy	2017	2021	H. Levison/SwRI	Goddard	LM Denver	Jupiter’s Trojan asteroids
Psyche	2017	2023	L. Elkins-Tanton/ ASU	JPL	JPL	Psyche

Abbreviations
APL Applied Physics Laboratory, Johns Hopkins University
ASU Arizona State University
CIW Carnegie Institution of Washington
CONTOUR Comet Nucleus Tour
GRAIL Gravity Recovery and Interior Laboratory
InSight Interior exploration using Seismic Investigations, Geodesy and Heat Transport
JPL Jet Propulsion Laboratory, California Institute of Technology
LM Lockheed Martin
MESSENGER MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MIT Massachusetts Institute of Technology
NEAR Near-Earth Asteroid Rendezvous
PS Project Scientist
SwRI Southwest Research Institute
UCLA University of California, Los Angeles
* InSight delayed from 2016 to 2018 Mars launch opportunity due to instrument problem

been JPL's, with the exception of Kepler, which came out of Ames, but NASA put project management at JPL, which was considered to have more capacity to deal with complex projects. Noteworthy also is that Mars does not appear between the first and the last chosen, because in 2001 the agency launched a parallel competition program for smaller missions to the Red Planet, Mars Scout. It chose two before it became a victim of SMD budget cuts and overruns on Mars Science Laboratory.[15]

From the standpoint of 2001, however, the Discovery program was already a smashing success for Goldin's faltering "faster, better, cheaper" campaign. In addition to Lunar Prospector, the NEAR Shoemaker spacecraft flew by asteroid Mathilde in 1996 and orbited and ultimately landed on Eros in 2000–2001 (after a near-fatal, in-flight emergency delayed the asteroid rendezvous by a year), and Mars Pathfinder made a spectacular, airbag-cushioned landing in 1997. Moreover, Stardust and Genesis launched and began to collect samples, and several new, exciting missions were in the works. The program had sustained an AO every other year since 1994 and had made five launches in five and a half years since NEAR in early 1996. Discovery's record of success with competitions and PI-led projects moved NASA not only to start Mars Scout, but also to revise the selection process for the Explorer program that inspired Discovery, and to begin contemplating such a program for mid-sized, outer-planet missions, New Frontiers.[16]

Discovery's Time of Troubles, 2002–2005

The program's visible troubles began on August 15, 2002, when the CONTOUR spacecraft disappeared near the end of its scheduled burn to leave a high-Earth orbit on a trajectory to intercept Comet Encke. Subsequent telescope searches turned up three possible objects. The review board ultimately blamed the impingement of the solid rocket's expanding plume on the spacecraft for its failure, although APL believed that an explosion in the older, "recertified" motor it had purchased was actually at fault. Tom Krimigis, then approaching the end of his tenure as APL Space Department head, describes the reviews and investigations as painful and onerous.[17] It hurt the laboratory's reputation as a reliable implementer of "faster, better, cheaper" projects and accelerated a cultural change in the Discovery program.

The embarrassing losses of Mars Climate Orbiter and Mars Polar Lander in 1999, plus several other failures in non-Discovery "faster, better, cheaper" programs, had already begun to increase OSS requirements for more intensive reviews and more elaborate oversight. NASA Independent Assessment Teams (NIAT—everything had to have an acronym) and NASA Program Requirement 7120.5, a systems-management instruction created in the mid-1990s, were required on all missions. The new reviews first become visible in available Discovery documents in March 2001. Deep Impact was formally considered for termination before the beginning of Phase C/D for technical troubles and overruns. Troubles were mastered to the extent that the program was ultimately confirmed in May. In the process, NASA added $8.7 million over the cap to account for new, more stringent review processes that had not been previously required.[18]

Immediately after the CONTOUR failure, problems in the program multiplied. MESSENGER, which was also being developed and built by APL, began to run into schedule pressure due to late delivery of components and technical challenges with its lightweight structure, propulsion system, and innovative ceramic fabric heat shield to protect the spacecraft from intense solar heating at Mercury. The March 2004 launch date begin to look problematic. Deep Impact's cost overruns led to another termination review in October 2002, although it survived that one too. There were also warning signs of future technical problems with the Kepler telescope, which had very stringent optical and charge coupled device (CCD) requirements in order to make it capable of detecting extrasolar planets down to Earth size. Those challenges would ultimately lead to large cost increases. In addition, questions arose about the Dawn mission, which would use solar-electric propulsion to visit two of the largest main-belt asteroids, Vesta and Ceres. In hindsight, it becomes apparent that Discovery's success in the 1990s had led the review and selection committees to accept very ambitious and complex proposals with a very high science return on budgets and schedules that were quite optimistic. Several program insiders have commented on MESSENGER, which was not only to fly by Mercury but also go into orbit around the planet with seven scientific instruments, a package worthy of a medium-class mission. It was much more complex and scientifically ambitious than Lunar Prospector, or even NEAR and Mars Pathfinder.[19]

Concern also grew in 2002 about the general state of the program. David Jarrett, who had been program manager since 1999 at a new Discovery office created in the NASA Management Office at JPL, noted in September that the budget was already overcommitted and that a FY 2002 shortfall had been covered by "borrowing" from other NASA programs. The prospective gap worsened from FY 2005 and beyond, and that did not even account for the unknown total expense of Kepler.[20] It is unclear when OSS, now led by Edward Weiler, decided not to issue a Discovery AO for 2002, but it must have been at least a year earlier.

When NASA finally issued one in 2004 it led to a failed process. According to Wes Huntress, who had left the agency in 1998 for the Carnegie Institution of Washington and who had served as President of the Planetary Society in the early 2000s, the AO's funding profile was "backloaded"—meaning a lot of the money would come later, rather than early in the development phase when it was needed—leading to "unachievable cost profiles and launch dates." Nothing would be selected except a "Mission of Opportunity" proposal for a US instrument on a lunar orbiter developed by India, Chandrayaan 1. The Solar System Exploration Division had created that new line in 1998, with budgets limited to $35 million. It was a response to the fact that all spacecraft missions were being proposed right up to the cap, as proposers and selection committees favored as much science as could be squeezed in for the money. An overview of Missions of Opportunity can be seen in Table 10.2.[21]

In 2003 and 2004, the technical troubles of the Discovery program only worsened. In addition to the ongoing troubles of Deep Impact and Kepler, MESSENGER's overruns and delays led a busted cost cap and to two launch window postponements in 2004, from March to May, and then to August. NASA required the last delay because the independent review teams were not confident in the autonomy system of the spacecraft, which would respond to problems and emergencies before Earth could be contacted. More testing was required. The new window had a major impact on the mission—Mercury orbit would come almost two years later, in 2011, requiring an entirely new trajectory and a considerable increase in its long-run operational cost. This change was questioned by some APL veterans, who viewed the delay as caused by NASA's excess caution. Whether it saved an ultimately very successful mission is unknowable, but the delay certainly reflected an agency more afraid of failure.[22]

Table 10.2 Discovery Missions of Opportunity

Name	*Selection*	*Launch*	*Principal Investigator/ Institution*	*Lead Center*	*Spacecraft*	*Target*
Aspera-3 (instrument)	1998	2003	D. Winningham/ SwRI	SwRI	Mars Express (ESA)	Mars
NetLander instruments	2001	Canceled	W. B. Banerdt/ JPL	JPL	NetLander (France)	Mars
M3 (instrument)	2005	2008	Carle Pieters/ Brown University	JPL	Chandrayaan 1 (India)	Moon
EPOXI	2007	2005	M. A'Hearn/ University of Maryland	JPL/ Ball	Deep Impact bus	Extrasolar plan-etsComet Hartley 2
Stardust-NEXT	2007	1999	J. Veverka/ Cornell	JPL	Stardust bus	Comet Tempel 1
Strofio (instrument)	2009	2018?	S. Livi/SwRI	SwRI	BepiColombo (ESA)	Mercury

Abbreviations
Aspera Analyzer of Space Plasma and Energetic Atoms
EPOXI Extrasolar Planet Observations and Characterization (EPOCh) and Deep Impact eXtended Investigation (DIXI)
ESA European Space Agency
M3 Moon Mineralogy Mapper
Stardust-NEXT Stardust-New Exploration of Tempel 1
SwRI Southwest Research Institute

The overruns on several projects led planetary division director Colleen Hartman to issue a new requirement in spring 2003 that a cost reserve of 25 percent be carried on all future proposals. In November, Kenneth Ledbetter, one of Weiler's deputies, stated that the Discovery program was no longer the "poster child of NASA's Space Science activity." It "was rapidly gaining a reputation for cost overruns, schedule delays, broken promises and even failures." Reviews indicated that the program management structure was not working well. Jarrett had a very small number of civil servants in his office in Pasadena, supported by a separate office of JPL employees (who worked for Caltech), but it was hard for the laboratory to get good people in those positions. "Program executives" and "program scientists" overseeing the various projects, but having no control over budgets, were still located at NASA Headquarters, dividing responsibility further.[23]

OSS decided to consolidate management in a single JPL office and "firewall" its staffers from the parts of JPL engaged in missions and proposals. Additional support and analysis was to come from the non-profit Aerospace Corporation. JPL Director Charles Elachi appointed an experienced project manager to take over the office, but the whole move proved abortive. By the end of 2004, the Discovery and New Frontiers Office (they had been combined shortly before) was transferred to the Marshall Space Flight Center in Huntsville, AL. The sources are unrevealing, but there was dislike of Aerospace's meddling and JPL's apparent conflict of interest. The new program manager at Marshall, Todd May, had to work to build credibility and confidence in his office, as Marshall had almost no experience or investment in planetary exploration—precisely the neutrality that was desirable to many.[24]

As if to punctuate Discovery's public embarrassments, after the return capsule from the Genesis solar-wind sampling mission reentered the Earth's atmosphere on September 8, 2004, its parachute failed to open. It crashed into the Utah desert, contaminating and partially shattering its sample surfaces. It appeared that NASA and Discovery had failed again. Subsequent analysis revealed that an accelerometer sensor the size of a pencil eraser had been installed upside down by the contractor and testing had been inadequate to reveal the error. It was essentially the same landing system as the one on Stardust, launched earlier, so concern grew that its return was compromised too. (Its testing had been more extensive and there were no problems during landing on January 15, 2006.) The public came away with the impression that Genesis had been ruined, but in fact many of the sample surfaces were intact and the contamination was easily detected during analysis. Indeed, Genesis met virtually all its scientific objectives and delivered important new insights into the isotopic composition of the Sun and how it differed from the Earth's. The spectacular success of Deep Impact's "impactor" capsule crashing into Comet Tempel 1 on the July 4, 2005, further lifted program spirits and reputation. The main spacecraft returned amazing pictures and data about the comet's structure and composition.[25]

Discovery 2.0, 2005–Present

Out of the crisis emerged version two of the Discovery program. The PI-led competitive selection and the goal of producing lower-cost planetary missions, mostly to inner solar system targets, remained, but all of the "better, faster, cheaper" objectives of the original program were thrown overboard or eroded away. The development time of 36 months was increased to 45–51 months. Budget caps on several missions had been violated without any being terminated. Spacecraft and mission development was to be handled under elaborate systems management regulations, with multiple independent reviews. Highly paid personnel had to spend countless hours producing reports and viewgraphs and then sit in meetings discussing them. APL, notably, was forced to evolve away from its traditional, paperwork-light methods and operate more like JPL, with more NASA oversight and intervention, much to the distaste of APL veterans like Tom Krimigis. It raised the question as to why competing centers were even needed, if their management models were all alike. Perhaps not coincidentally, JPL became dominant as lead center for missions, as it reorganized to support multiple Discovery proposals that fit NASA's desired management model.[26]

More elaborate proposals and reviews meant that final selections of new spacecraft missions from AOs took longer—about two years instead of one—and became few and far between for budgetary reasons. As noted earlier, there were only two new Discovery missions approved in the fourteen-year period after 2001. The less expensive Missions of Opportunity have partially compensated for the shortage of full mission proposals seeking funding below the cap, yet the monetary cap on spacecraft missions has grown significantly above the rate of inflation. In the AO of 2014 it was $450 million without launch; Discovery's original $150 million cap would be about $253 million in 2014 dollars (Fig. 10.2).[27] In short, a small planetary mission is now around a half a billion dollars.

On the other hand, the program has rung up a series of scientific and technical triumphs, largely from missions picked between 1995 and 2001: Stardust returned comet dust samples, MESSENGER flew by and then orbited Mercury for years, Dawn has used its innovative solar-electric propulsion to orbit two major main-belt asteroids, and the Kepler telescope (which was transferred out of the Discovery program in its operational phase) has found hundreds and perhaps thousands of new planetary systems, some with objects near Earth sized. GRAIL, picked in 2007 from a much-revised 2006 AO, produced new insights into the structure of the Moon. Mission of Opportunity funds allowed the launch of American instruments on foreign planetary spacecraft and the creative redeployment of the Stardust and Deep Impact main-bus vehicles for other objectives. Thus the second iteration of Discovery has been just as

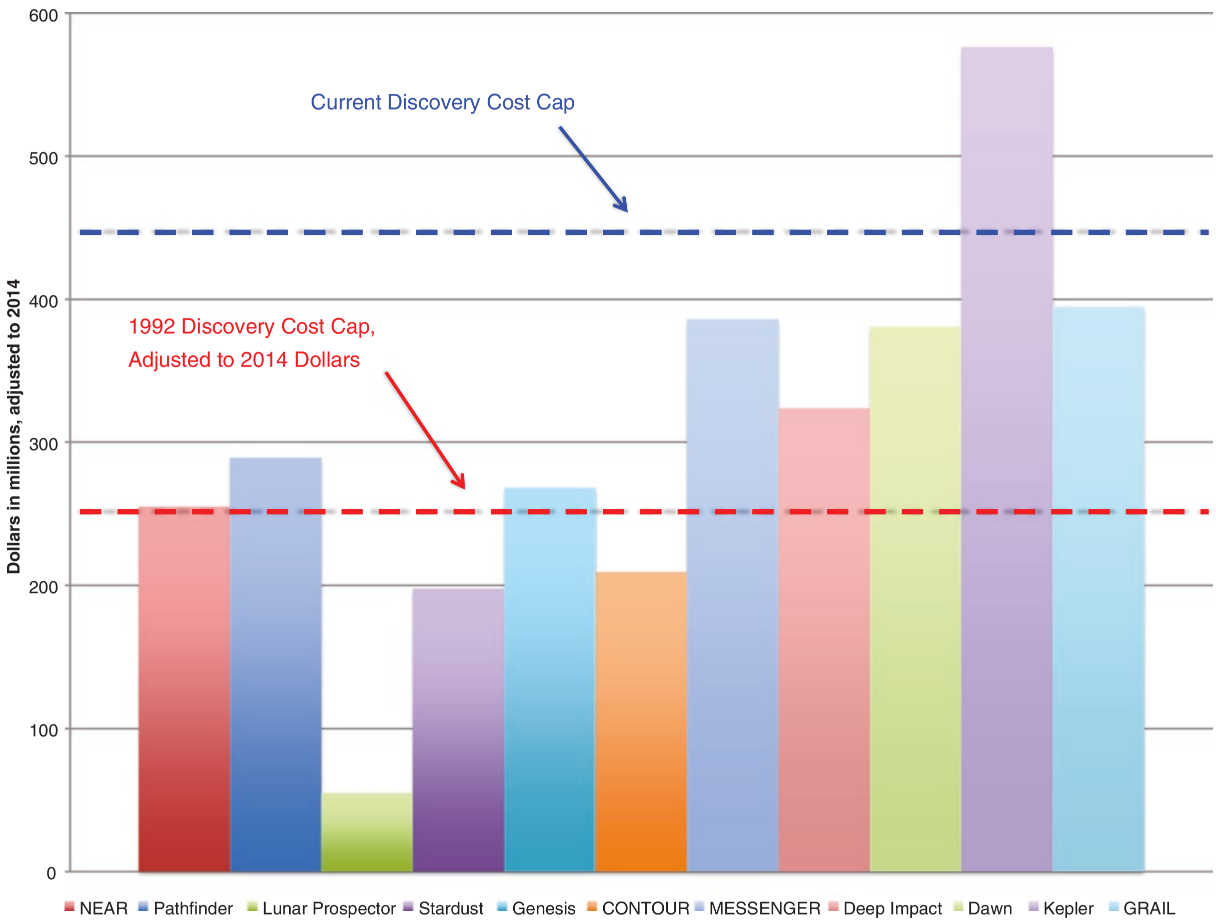

Fig. 10.2 Costs of NASA Discovery missions. (Courtesy of Jason Callahan/Planetary Society.)

successful as the first. It has produced rich scientific results with spacecraft more sophisticated and more long-lived than was expected at the beginning.[28]

Many of Discovery's budgetary problems were not self-generated. In addition to NASA leadership's pressure to avoid failures that might lead to public and political embarrassment, Administrator Mike Griffin took $3 billion out of the long-term space science budget to pay for President George W. Bush's Moon–Mars human spaceflight program, according to Wes Huntress. There were also large overruns on Mars Science Laboratory and the Webb Space Telescope. Moreover, the Delta II was phased out as obsolescent and launch vehicle prices increased for all programs. Discovery's launch costs rose to over $80 million in the early 2000s and are now of the order of $100 million.[29]

One of the side effects of the greatly reduced selection rate is that it became nearly impossible for a proposal highly ranked in one competition to win in a later one, as Genesis and MESSENGER did in the 1990s. The proposal-writing effort has become too massive and the odds too poor because of the few selected. The current planetary division director, James Green, has been trying to return Discovery to a more frequent AO schedule. Yet given the increased expense of a mission, and the lack of interest within NASA in going back to riskier development methods, it does not seem at all likely that the rate can be accelerated that much. Indeed, given the elaborate review and the quality of the proposals, he decided to make two selections in 2017, which means skipping the next AO cycle and waiting several years for another.[30]

Discovery and Innovation at NASA

Discovery remains an important and influential program in the history of space science at NASA. It expanded the number of missions funded on a standing budget line, rather than one "new start" at a time, and it pioneered the competitive bidding of entire spacecraft missions by PIs, its most important innovation. That model led to the reform of the Explorer program that inspired it, and the creation of New Frontiers and the more short-lived Mars Scout. This organizational innovation resulted in many imaginative missions. Mars Pathfinder took on a risky Mars landing based on difficult-to-test airbags, but it was really a technology demonstration, not a science mission. Most missions grew out of competitions where, as intended, the science output was the chief driver in design and selection, although some did include noteworthy technological innovations: Stardust used a marvelous, ultralight "aerogel" to stop cometary particles; Dawn became the first spacecraft to use ion propulsion as the basic propulsion for an interplanetary mission; Deep Impact smashed a hole in Comet Tempel 1; MESSENGER was protected by a new ceramic fabric heat shield. However, funding the development of cutting-edge technology was never the program's purpose. Such lines existed elsewhere in NASA, but, like the New Millennium program, tended to come and go and not necessarily work well in the absence of a specific mission objective. The Discovery program demonstrated that open competitions could lead to innovation, although it was most often in project organization or the imaginative use of technologies on the cusp of readiness.

If mission competitions were Discovery's longest-lasting influence on NASA, clearly its original development methodology was not influential. Of course, that was only part of the larger story of a space agency briefly willing to take risks, and then shrinking back from the consequences of a series of failures in 1999—although Discovery was not very visibly affected until it ran into its own crisis in 2002. The program was a milestone in lowering the cost of planetary exploration, by sustaining a line of relatively cheap and innovative missions. Nevertheless, after the flight from risk was compounded by inflationary increases beyond NASA's control, the definition of relatively cheap got revised sharply upward, as shown by mission caps that are nearly double when accounting for inflation.

The two most influential early founders of Discovery, Tom Krimigis and Wes Huntress, are now very critical of the agency's unwillingness to take risks, but they take pride in the scientific output of Discovery, which has been stellar. They are reluctant to admit, however, that that was achieved in part by taking on ambitious missions that pushed the low-cost model to its breaking point. They and others praise the program's impact on the planetary science discipline, both in the sustained production of new data and in its power to nurture graduate students and postdocs in their career training and development. In contrast to the difficult situation of the 1980s, where long gaps in new data were punctuated by a handful of very expensive flagship missions, Discovery has succeeded, alongside NASA's Mars program and a handful of outer-planets missions, in keeping up a continuous flow of new data for almost two decades.

Is there an option to return to a riskier, less bureaucratic Discovery program? Clearly it is possible, but does not seem at all likely. As Howard McCurdy has shown in his examination of the fate of "faster, better, cheaper," both high-cost and low-cost approaches to spacecraft development can work.[31] Discovery's history alone demonstrates that point. Yet the low-cost approach, while saving much money, is more likely to produce failures, which the current agency leadership, and the US political system to which it reports, seems unwilling to contemplate. One scientist has commented that the current environment is encapsulated in a community joke: "Dare to fail … but don't fail!"[32] After a quarter-century, Discovery still appears to be thriving, but that mantra is likely to remain its guiding principle for the foreseeable future.

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it came from human spaceflight: SMK OHI by MJN, 24 July 2015. However, Jason Callahan of the Planetary Society believes that it began as a guideline in 1996 to unite the disparate systems-management standards of NASA centers and only later became mandatory. J. Callahan phone conversation with MJN, 12 November 2015.

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CHAPTER 11

Partnerships for Innovation: The X-33/ VentureStar

Howard E. McCurdy

At the height of the Apollo program to land Americans on the Moon in the 1960s, Robert Gilruth called in Max Faget and urged him to "get off this blunt-body, parachute stuff. It's time we thought of landing on wheels."[1]

Gilruth was director of NASA's Manned Spacecraft Center (renamed the Johnson Space Center in 1973), Faget his chief engineer. The two had worked together as members of the Pilotless Aircraft Research Division, a small group of aeronautical engineers employed at the Langley Research Center before NASA was formed. The engineers built spacecraft models and launched them from a test facility at Wallops Island, VA. They tested hundreds of models to see how vehicles of various shape would perform while flying through the atmosphere.[2] In 1958, when NASA was created, Gilruth and Faget joined 33 other engineers in what was known as the Langley Center's Space Task Group. Faget designed the blunt-shaped Mercury space capsule that landed with indignity in the ocean after reentering the atmosphere. The capsule design evolved into the Gemini, Apollo, and Orion spacecraft.

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In his heart, Gilruth remained an aeronautical engineer. As a boy, he built model airplanes. During the Great Depression, he earned bachelor's and master's degrees from the University of Minnesota in aeronautical engineering.[3] Faget was a mechanical engineer.

Gilruth favored spaceships of the popular imagination that had wings or vanes, devices designed to control their movement through planetary atmospheres. Such spacecraft landed on wheels or at least touched down on their tails. In 1946, Langley engineers established a west coast flight center to test X-planes, hybrid vehicles that flew very fast and very high, eventually to the edge of space. The gumdrop-shaped capsule that Faget designed for Project Mercury violated this tradition. It looked like a warhead, the shape from which it was derived.

In 1972, Gilruth, Faget, and their human flight colleagues received permission to begin work on a spaceship with wheels and wings. The people who designed and built what became the NASA space shuttle assumed that it would be the first in a continuing series of airplane-like space craft, ever improving in capability and ease of flying.

If the Mercury/Gemini/Apollo space capsules could be considered a deviation from the true form, the space shuttle could be placed in the first generation of true spacecraft. A second generation would follow; then a third. Flight advocates hoped that the second-generation spacecraft would so improve on the capabilities of the first that the new vehicle could reach space with a single stage. The second generation would require no external structures, like fuel tanks or rocket boosters. Its engines and fuel tanks would be placed on the inside. It would fly like a rocket ship and land like a plane.

The second-generation concept looked great on a painter's canvas. It produced marvelous space art. Actually building the new space ship proved more daunting, however. To overcome the challenges of constructing one, NASA officials adopted an unconventional approach. They dropped the orthodox model of government contracting that had produced previous space capsules and the NASA space shuttle. In its place, the officials entered into a public/private partnership.

Chasing the Wedge

A public/private partnership differs from a conventional government contract in a number of ways. In a conventional contract, the government supplies most or all of the funds. The contractor completes the work and delivers the service or product to the government, which owns and uses the result. In a partnership, both parties typically contribute funds. Both risk losing money if the undertaking fails. If the activity succeeds, the private partner or a separate authority usually owns the product, which it can sell commercially and charge other partners to use.

Municipal governments use partnerships to construct facilities like sports stadiums and parking garages. State governments use the form for transportation projects like toll roads and tunnels. During the late twentieth century, it was not a familiar form for space travel.

Such an arrangement applied to a second-generation spacecraft possessed an important advantage, nevertheless: it made the undertaking much easier to finance. NASA officials originally intended to fly their conventionally produced space shuttle for twelve years, from 1978 to 1990. According to the original plan, flight engineers would spend eight years and $5.15 billion designing the spacecraft, fabricating its components including two orbiters, and testing the vehicle. Additional expenditures of $2.9 billion would occur as the agency brought the total number of orbiters to five and made additional investments.[4] Expenditures for spacecraft development would wind down as space flight operations ramped up.

In the original plan, NASA would conduct 580 flights of its reusable space vehicles.[5] At an average cost of $10 million per launch, and an average flight rate of 48 launches per year over twelve years, the typical annual budget for spacecraft operations would not exceed $500 million. By assigning the expense of shuttle operations to specific missions, NASA officials would free up at least $5 billion: the additional amount of money that they would save by not needing to procure more expensive expendable launch vehicles. Moreover, many of the shuttle flights would be reimbursable—commercial or military payloads for which other parties would pay. The end of development, the planners envisioned, would create a fiscal wedge that could finance something else.

Something else would be a permanently occupied space station to which the first-generation space shuttle could fly. In 1983, NASA officials offered an estimate for fabricating the components of an orbital space station: $8 billion.[6] According to the original plan, expenditures would be spread over seven years, peaking in 1989 at nearly $3 billion and ending by 1991.

Development of the shuttle slipped by three years, with the first test flight occurring in 1981. For a twelve-year cycle, that placed the

Table 11.1 Planned and actual costs of NASA space shuttle during the last five years of projected operations (real-year dollars, in millions)

	1989	*1990*	*1991*	*1992*	*1993*
Planned					
Vehicle	326	102	0	0	0
Launch	1501	1875	1942	2043	2129
Actual					
Vehicle	1122	1195	1314	1296	1053
Launch	2546	2493	2752	3029	3000

Source For planned outlays: Klaus P. Heiss and Oskar Morgenstern, Economic Analysis of the Space Shuttle System: Executive Summary, NASA Contract NASW—2081, January 31, 1972, Table 0.4, Life Cycle Cost Summary Data, Space Shuttle System. Planned outlays stated in 1970 dollars, converted to actual real-year dollars using the NASA New Start Inflation Index

anticipated last year of shuttle operations at 1993. The end of shuttle development opened the wedge into which the space station would fly. The end of station development created a wedge that could finance the creation of a second-generation shuttle. By then, the wedge would grow to about $2 billion per year. A judicious use of development funds built on advances in technology would put the USA on the path toward a replacement vehicle with little effect on the nation's overall civil space budget.

The plan worked well on paper, but not in practice. First, shuttle development outlays did not end. As Table 11.1 reveals, shuttle engineers continued to spend money on vehicle maintenance and upgrades. Under the original plan, those expenditures should have dropped to just $326 million (real-year dollars) in the eighth year of shuttle operations (1989). In fact, they continued unabated at a level exceeding $1 billion per year. That cut the anticipated $2 billion wedge in half.

Secondly, operating expenses exceeded expectations. Instead of flying 580 times over twelve years, NASA flew the space shuttle 135 times over thirty-one years. The last shuttle flight, anticipated to take place in 1993, did not occur until 2011. Operating fewer flights on a fixed expenditure base caused the operational cost per flight to rise from $10 million per launch (estimated 1971 dollars) to $407 million per launch (real-year dollars) by FY 1995. On an annualized basis, that took another $1 billion out of the wedge. Now the wedge was gone.

Table 11.2 Planned and actual expenditures for the development of the *Freedom* space station (real-year dollars, in millions)

	1985	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*
Planned	233	288	1153	2585	2960	1931	424	–	–
Actual	156	200	433	395	903	1807	1963	2136	2241

Source Peggy Finarelli (NASA) to Bart Borrasca (OMB), Space Station Funding, September 8, 1983. Planned outlays stated in 1984 dollars, converted to actual real-year dollars using the NASA New Start Inflation Index

To compound the loss, space station development expenditures did not follow the expected pattern. Instead of peaking in 1989 and falling to zero by 1992, development outlays continued to grow past $2 billion (Table 11.2).

Constant redesign caused NASA to exhaust all of the planned $8 billion development outlay without completing the expenditures necessary to fabricate what eventually became the International Space Station. The anticipated wedge fell from $2 billion to zero and then to a $2 billion deficit.

Yet the story did not end. The cost of operating the enlarged space station had to be accommodated. Budget officers estimated that the station would cost $1.5–2 billion per year to operate by the first decade of the twenty-first century.[7] NASA's twin sisters—the space shuttle and station—essentially ate the funds that might have financed a shuttle replacement.

The consequence of these events became clear. Expenditures on the space shuttle and the continuing agonies of the International Space Station crowded out funds that otherwise could be deployed on the development of a second-generation vehicle. In the 1990s, NASA officials could not afford to trade a less than perfect space shuttle for a second-generation model.[8] They needed to finance the new model in an unconventional way.

Planning by Budget

Completion of the original shuttle replacement plan required a level of strategic planning and fiscal discipline at which the civil space agency proved entirely inept. To be fair, the fault lay more with systematic flaws in the federal budget process than with the inability of agency managers to engage in long-range planning. Nonetheless, NASA officials participated in the process that maintained those flaws. The process can be described as follows.

Demand for tax-financed public services always exceeds their supply. That is a basic feature of public-sector economics. So long as public activities like space flight are priced at a level below their market-clearing level, people will continue to demand more than the government can possibly provide. Despite remonstrations from the community of space advocates to the contrary, the civil space budget can never be enough.

Absent an effective process for strategic planning, new starts arise when lines for financing them appear in the annual budget. This leads to a process wherein program advocates seek commitments for large undertakings by adding small expenditures to an upcoming appropriation. Once in the budget, the outlays become part of the agency base. The pressure to attach additional elements to those elements can prove irresistible (Fig. 11.1).

In 1985, NASA officials received authorization to construct Mars Observer, the first US satellite to visit that planet in fifteen years (dated from its expected date of arrival). Program advocates viewed the proposed instrument as a relatively simple, $213 million low-cost orbiter, beginning with a first-year appropriation (after approval) of $34 million. Scientists viewed the mission as a rare opportunity to study Mars. The satellite grew in scale and complexity until the cost topped $800 million. As the spacecraft approached Mars in August 1993, it disappeared. A special investigating committee traced the loss to a leak in the propulsion system that caused a small explosion during the pressurization sequence prior to orbital insertion.[9] Broadly speaking, the program grew too big for the resources available to manage it.

Similar events afflicted the agency's space shuttle, space station, and Moon–Mars initiatives. The space station program grew from a simple four-module outpost realistically priced at $12–14 billion to something so complex that the government spent the original cost estimate for development simply redesigning it. The Moon–Mars initiative—also known as the Space Exploration Initiative—proved especially painful. Originally proposed in 1989 as a vehicle for breakthrough technologies, it turned into a $1 trillion agency initiative that solidified the NASA space shuttle, protected the emerging space station, and expanded the agency's existing field centers.[10]

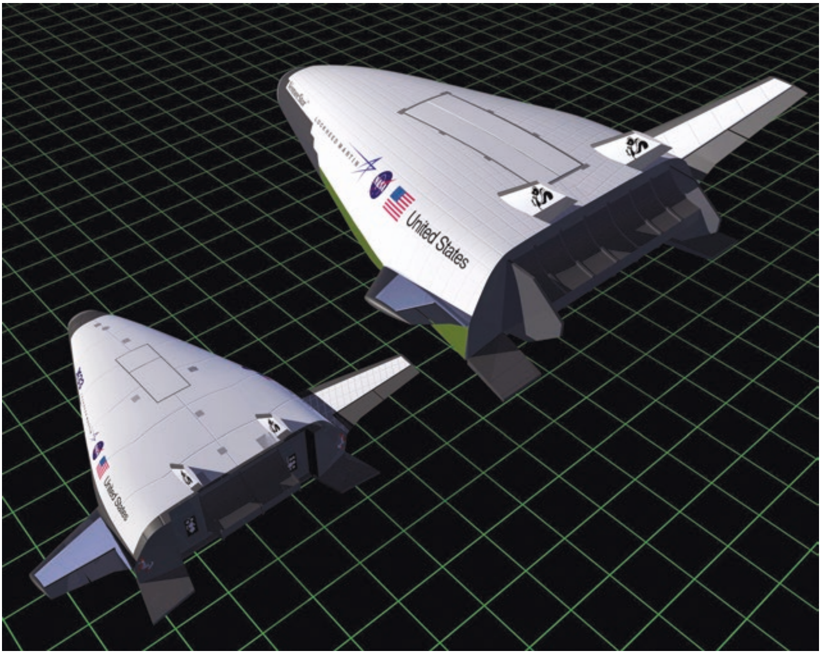

Fig. 11.1 The X-33 sits next to the larger VentureStar vehicle in this artist's conception of the two spacecraft that never flew. (NASA, image number ED97-43938-1, public domain. (Available at https://www.dfrc.nasa.gov/Gallery/Photo/X-33/HTML/ED97-43938-1.html))

Reaction to the Space Exploration Initiative resulted in the removal of the NASA Administrator, shuttle astronaut Richard Truly. In his place, the White House offered the cost-conscious and somewhat eccentric Daniel S. Goldin. What Goldin discovered upon his arrival in 1992 startled him. There was simply not enough money in the NASA budget to do anything new.

The NASA wedge strategy did not work well under these circumstances. The practice of winding down one program and using the funds to finance another ignored fundamental features of the process for setting national priorities through the budget approval process. Regardless of the cause, the consequences were the same. NASA simply did not have the money to mount a shuttle replacement development effort on the scale of the original shuttle program.

Single Stage to Orbit

The search for a shuttle replacement was part of a larger effort to enhance the nation's launch capabilities. More than one agency was involved. The breadth of interest in better launch proficiency provided a number of pathways from which NASA officials could choose. One such pathway broadened the funding base from which the funds would be drawn. If NASA could not afford a shuttle replacement, perhaps some other organization could. Ultimately, this approach proved unsuccessful too.

Two years after announcing his support for a permanently occupied space station, President Ronald Reagan used his 1986 State of the Union Address to embrace the concept of a National Aero-Space Plane (NASP). Reagan called it "a new Orient Express that could, by the end of the next decade, take off from Dulles Airport and accelerate up to twenty-five times the speed of sound, attaining low earth orbit or flying to Tokyo within two hours."[11]

The NASP initiative utilized a conventional approach to government research and development. Congress provided funds to NASA and the Department of Defense. Those agencies in turn hired contractors to conduct basic research. NASP researchers tackled the challenging dynamics of propulsion and material physics. They worked on engines designed to change their method of operation as the aero-space plane flew high and low. The researchers produced structures that could withstand a wide range of temperatures, from the heat of atmospheric friction to the frigidity of cryogenic fuel containers.

According to one source, the US government admitted to spending $1.7 billion on technology research before canceling the project in 1993. Other sources place the outlay at $3.3 billion. While 80% of the funding made its way through the US defense budget, the program also drew on a previously heavily classified initiative known as Cooper Canyon undertaken in 1982 by the Defense Advanced Research Project Agency (DARPA). Some experts suggest that the government spending necessary to build a workable commercial or military vehicle would have reached $30–40 billion. Others say that it was a technology "way ahead of its time."[12]

The program never achieved its objective of building two experimental models, one of which was to fly through the atmosphere and into space in a single stage. Yet it did establish the precedent that a shuttle replacement might be financed by pushing the bulk of the expenditure onto the more broadly spread national security budget.

Spaceplane advocates utilized the national security approach again in 1990 when work began on the DC-X, otherwise known as the Delta Clipper. Monies initially flowed through the Ballistic Missile Defense Organization (BMDO). Defense analysts anticipated that any space-based missile shield would need to be serviced by flight vehicles that were cheaper and more reliable than NASA's space shuttle, which by then had suffered one major catastrophe and a sluggish flight rate.

Clipper advocates presented a relatively simple design that could be constructed from existing technologies. The vehicle would take off and land on its tail. A fully qualified flight vehicle would reenter the atmosphere nose first, then rotate and land tail down. The McDonnell Douglas Corporation won the contract to build a prototype, a one-third scale model that actually flew. The company completed 12 test flights, the highest to an altitude of 1.9 miles (3140 meters). The test model rose with its nose pointed skyward and returned the same way. On the 12th flight, the returning model tipped over when a landing strut failed to deploy. The vehicle exploded.[13]

The BMDO, Department of Defense, and NASA provided funds for the endeavor, just modest amounts. The agencies declined to supply more after the 12th flight when the vehicle was destroyed. The program provided useful information and solidified the presumption that while the government might provide initial funding for technology development, it was unlikely to produce additional funding for full-scale production.

In spite of these setbacks, enthusiasm for the single-stage-to-orbit (SSTO) approach remained high. In 1993, the NASA Administrator instructed a special in-house team to review options and opportunities in the launch sector. The team produced what was known as the Access to Space Study. Team members reviewed three main options: the government could upgrade the space shuttle, it could develop new expendable launch vehicles, or it could develop an entirely new reusable launch system. The subgroup studying the third option made a powerful argument on behalf of a launch vehicle that could reach space and return in a single stage. The whole committee agreed: "The study concluded that the most beneficial option is to develop and deploy a fully reusable single-stage-to-orbit (SSTO) pure-rocket launch vehicle fleet incorporating advanced technologies, and to phase out current systems."[14]

Commercial Space

Concurrent with the optimism about SSTO vehicles, a number of aerospace companies expressed interest in the objective of developing and flying their own rocket craft. At the time, the only avenue to space ran through government agencies. Gary Hudson, a rocket engineer, complained that established government bodies that might fund new launch technologies resisted new ideas. He had kind words for the Strategic Defense Initiative Organization, but condemned the US Air Force and NASA: "It is in NASA's interest to take very small steps toward an ill-defined goal since such a policy can sustain the agency indefinitely." In 1993, he and a colleague from the American Rocket Company conceived of a design that merged the features of a rocket and a helicopter. Convinced that the government would never fund the idea, Hudson proposed they develop the concept commercially. In other words, they would enlist private investors with the promise that the company could sell the finished launch services to government and private users.[15]

Hudson had worked on the fringes of the aerospace movement, pursuing craft such as the Phoenix VTOVL, the Percheron, and the Conestoga. The Conestoga is reputed to be the first privately funded commercial rocket.[16] First launched in 1982, it flew twice. That same year, Hudson founded the Pacific American Launch Systems Company with plans to create a vertical takeoff and landing, SSTO vehicle. The spacecraft, known as Phoenix, came in two versions: a smaller cargo vehicle and a larger excursion model for personnel. After a few years, Hudson and his business associates disbanded the company when they failed to attract an adequate number of investors.

Hudson subsequently founded Rotary Rocket, which likewise failed to attract sufficient investors to develop its oddly constructed Roton. This curiously designed vehicle revived the helicopter–rocket concept. More importantly, the mood that Hudson and his colleagues represented laid the groundwork for an important shift in government policy.

Congress had enacted and Ronald Reagan had signed the Commercial Space Launch Act in 1984. The act declared that the technical skill needed to launch rockets into space was no longer solely restricted to government agencies. Private companies had acquired those skills too. The act authorized the US Secretary of Transportation to issue licenses and encourage the development of a commercial launch industry. (The act did not mention NASA.)

It may be hard to imagine today, but only the government provided launch services for the first quarter-century of spaceflight. By 2013, the industrial sector of space had grown worldwide into a multi-billion-dollar enterprise three times as large as all government spending.[17] Advocates of commercialization liked to point to the early financial support for rocket experimentation provided by philanthropic organizations such as the Guggenheim Foundation, which helped finance the work of Robert Goddard, as well as the growing private-sector interest in satellite communication.[18] Yet when the telephone companies (AT&T and Bell Telephone Laboratories) sought to establish the first commercial communications satellite in 1962, they needed NASA to launch the instrument. Said one commentator: "the commercial launch industry did not exist in any recognizable form."[19]

Interest in various commercial space activities grew rapidly during the late twentieth century. Entrepreneurs foresaw commercial opportunities in satellite communication, television and radio transmission, microgravity manufacturing, energy generation, crop control, and space tourism.[20] By one account, President Reagan decided to endorse a permanently occupied space station after meeting with a group of business executives touting commercial opportunities in space in the summer of 1983. In spite of the growing interest in space commerce, US policy until 1986 identified the NASA space shuttle as the primary launch vehicle for all US payloads—scientific, military, and commercial.

That shortly began to change. The European Space Agency challenged NASA's claims to commercial dominance with Arianes 4 and 5. The space shuttle *Challenger* exploded in 1986. The White House directed NASA to stop launching commercial satellites except in special circumstances. The US Air Force supported the production of its own line of expendable launch vehicles with both military and commercial applications.

A Partnership for the X-34

Concurrent with these developments, general interest in public/private partnerships began to grow. In 1988, David Osborne published the work on government innovation that would spur the *Reinventing Government* book and movement five years later. Osborne and co-author Ted Gaebler called on the government to stop relying on single-source public providers and deliver more services in conjunction with the private and nonprofit sectors.[21] In 1988, the state of Virginia authorized construction of the privately financed Dulles Greenway outside of Washington, DC. The same year, construction began on the tunnel between Britain and France. The operating entity is listed on the London and Paris stock exchanges. The concept was about to be applied to rocketry.

Interest in the use of public/private partnerships for rocket development emerged from a number of converging factors. NASA needed to work on a shuttle replacement, but did not have the funds to do it. Technological developments permitted consideration of SSTO launch vehicles. NASA and the Department of Defense had funded SSTO technology development efforts, although in a traditional government contract way. Space visionaries maintained their fascination with spacecraft that landed like airplanes, the shuttle experience notwithstanding. Worldwide, commercial space activities grew. Expenditures by private firms soon bypassed government spending in scale. (Analysts generally identify 1997 as the bypass year.) Government policies favored space commercialization and a few space entrepreneurs agitated to develop privately financed spacecraft. Interest in reinventing government grew and, with it, experimentation with public/private partnerships. A new NASA Administrator supported strategies that favored low-cost innovation. The earlier history of commercial aviation encouraged people to think about the same forces working to expand space travel.

Partnerships offered a pathway through the shuttle replacement maze. The administrative inspiration for this approach arose from the X-34, introduced in 1994 (Fig. 11.2). Although the X-34 followed the X-33 numerically, it preceded the latter in terms of time.

Structurally as well as administratively, the X-34 differed dramatically from the DC-X (Delta Clipper), which was under development at the same time. The Delta Clipper looked like a dumpy obelisk, a short version of the Washington Monument with neither wheels nor wings. It took off and landed on its tail. The X-34 looked like an airplane or, more precisely, a drone. Long and sleek, it had both wheels and wings. Pilots carried it on the undercarriage of a reconfigured jetliner, like the X-planes of previous lore.

Neither the DC-X nor the X-34 prototypes that the flight engineers built were designed to reach orbital speeds. Rather, they were designed to develop the technologies necessary to do so. Engineers called them "test beds." The X-34 was to test a Fastrac engine, composite airframes, and autonomous flight control systems. It was designed to require a minimal

Fig. 11.2 Though not successful, efforts to produce the X-34 test vehicle using public/private partnerships provided important lessons for the initiatives that followed. (NASA, image number EC99-45173-57, public domain. (Available at https://www.dfrc.nasa.gov/Gallery/Photo/X-34/HTML/EC99-45173-57.html))

ground crew and quick turnaround. Had it ever flown (it never did so independently), it would have lofted an upper stage capable of carrying a small payload to space. Test beds offered an inexpensive method to develop new technologies without the expense of building a full-scale vessel.

The DC-X was run in the conventional way, with government agents, standard contracts, and lots of paperwork. The X-34 program utilized a new approach, which NASA officials characterized as a cooperative agreement. Just as the X-34 tested new technologies, the cooperative agreement demonstrated fresh approaches to project management and funding in the national space program.

Under the proposed terms of the cooperative agreement, NASA planned to partner with an outside organization to develop a prototype leading to “a small reusable, or partially reusable booster that has potential application to commercial launch capabilities, which reduce launch costs to the customer to $5000 per pound or less, for 1 to 2 klb class payloads." Any entity could apply to partner with NASA on the project, although aerospace firms were the most likely applicants. NASA would provide half of the funds for the demonstrator; the partner would supply the other half. The proposed cost was modest by aerospace standards: only $140 million combining both shares. By participating, the selected entity would receive $70 million in government seed money; it would invest $70 million of its own funds. With this investment, the entity would learn what it needed to know to develop a small, commercially viable, low-cost launch vehicle.[22] Although the draft agreement was silent on this issue, the arrangement anticipated that the partner would build and market the full-scale vehicle with private funds based on the advantages conferred from having solved the major technological issues.

From the list of applicants, NASA officials selected the Orbital Sciences Corporation. Advocates of space commercialization founded the company in 1982 to provide alternative launch services, a history covered in Chap. 9. On March 30, 1995, representatives from NASA and Orbital signed a cooperative agreement to develop the X-34. "Flight tests for the X-34 are planned for late 1997, with launch expected by mid-1998," the official announcement prescribed. NASA agreed to supply its $70 million, to be paid as Orbital met a series of milestones. The commercial partner agreed to provide at least as much.[23]

The partnership, though groundbreaking, did not implement well. Orbital immediately encountered problems with the selection of an appropriate rocket engine. The NASA Administrator got involved. Engine difficulties prompted Orbital to reassess the business model for the undertaking. In January 1996, less than one year after signing the cooperative agreement, Orbital told its subcontractors to stop work on the X-34.[24]

NASA officials resurrected the X-34 later that year under a more conventional contract arrangement. The program continued until 2001. Project workers conducted three undercarriage tests (carrying the X-34 prototype under a Lockheed L-1011). The demonstrator never independently flew.[25] By mid-1996, the attention of NASA officials had turned to the X-33. Although the X-34 reached a programmatic dead end, it had an enormous influence on the contractual arrangements for the X-33.

A Partnership for the X-33

Had an advanced form of the X-34 ever flown, it would have carried very small payloads to space; one source suggests payloads in the 1000–2000 lb range.[26] The X-33 presented a different order of magnitude. Planners anticipated that the orbital vehicle built on the technical foundation of the X-33 would be able to launch shuttle-sized payloads.[27] It was a shuttle-class vehicle, in shape and in scale, though far more advanced than the shuttle in areas like propulsion and thermal protection. Most significantly, it would fulfill the dream of an SSTO design. Shaped like a triangle with stubby wings, in one piece it would take off like a rocket and land like a plane.

Development of such a vehicle required a shuttle-type effort. The initial $5.15 billion development plan for the space shuttle translated into $23 billion in 1996 aerospace dollars. NASA officials simply did not have such funds. To jump-start the X-33, they turned to the cooperative agreement for the X-34 and modified it in the following ways.

As with the X-34, NASA planned to provide seed money to an industrial partner that would complete the basic design. The government would provide more money this time and a larger share. NASA officials anticipated that they could make this business plan work with an initial appropriation (seed money) of about $1 billion. The industrial partner would contribute a few hundred million dollars. Once the prototype flew, the financial arrangement would change. The partner would raise the funds necessary to construct the orbital vehicle. To help the partner raise sufficient funds from private investors, NASA promised to use vehicle when done. The partner would own the fully developed flight vehicle and could sell launch services to other customers, a further source of revenue from which it could repay its investors. This latter process was much more explicitly stated in the X-33 review procedures than with the X-34. As part of their proposal package, industry finalists were instructed to provide business plans that described how they could finance a full-scale rocket and make it pay.

Spread over four or five years, the government contribution would fit inside NASA's crowded list of fiscal priorities. It was certainly cheaper than attempting to finance another shuttle-class development program using conventional contracting methods. In concept, the government would not need to make major outlays until the vehicle was ready to fly and the government ready to purchase its service.

In January 1995, NASA invited interested parties to submit proposals. Three finalists emerged. In March, NASA officials signed cooperative agreements with the three. The cooperative agreements provided $7 million to each finalist and up to 15 months for each to prepare a detailed plan. Each finalist was expected to match the government's initial contribution with its own funds.[28]

Plans arrived the following spring, in 1996. A team led by the McDonnell Douglas Corporation proposed a vertical takeoff and landing configuration based on its DC-X program already underway. The Space Division at Rockwell International, which had built the shuttle orbiter, proposed a design that drew on its previous work: a long tube-shaped fuselage, relatively small delta-shaped wings, and two prominent tails.[29] NASA officials selected the submission from the Lockheed Martin Aerospace Company, whose design looked otherworldly, like a flying triangle. It utilized a lifting body shape that could take off like a rocket and land like a plane. NASA engineers had experimented with lifting bodies since 1962, stubby vehicles that relied upon the body of the aircraft to produce lift.

Vice President Al Gore announced the selection on July 2, 1996. NASA Administrator Dan Goldin presented the plan as a shift in government philosophy, one that got NASA out of the costly business of operating spacecraft and deeper into the realm of technology development. "The RVL program is a radical departure from the way NASA has done business in the past," Goldin added. "Our role is to develop the high risk technologies that industry cannot afford. But we won't build the vehicle, industry will."[30]

The finished vehicle would require a ground crew of "dozens, not thousands of people," Goldin professed. Launch preparations would take days, not months. Reliability would increase tenfold. Launch costs would fall to $1000 per pound. "You don't have to be a rocket scientist to understand the importance of this moment," said Gore.[31]

Commentators suggested that NASA picked the Lockheed Martin proposal because "it was the most daring and innovative."[32] Both administratively and technically, that was certainly the case.

Administratively, the cooperative agreement for the X-33 had certain distinguishing features. A traditional government contract can be characterized through what observers classify as a principal/agent relationship. A principal (the government) hires an agent (the contractor) and pays the latter to complete a specific job. To the best of its ability, the principal supervises the work of the agent, or at least specifies the scope of the work to be done.

A cooperative agreement creates a partnership. The partners are equal. They work together and share facilities. Both parties contribute resources to the project: people, capital, and equipment. The cooperative agreement for the X-33 called upon NASA to provide $912 million. Under the terms of the original agreement, Lockheed would provide $211 million more. NASA additionally provided noncash contributions by allowing its facilities and workers to be used.[33] While the agreement vested overall management responsibility with Lockheed, NASA personnel provided technical assistance. This created a different style of supervision, more lateral than vertical. Both sides gathered information about project progress by watching what their colleagues accomplished. An outside review body observed:

> In traditional research and development contracts, NASA sends personnel to contractor facilities to perform an extensive review of whether the contractor performed its assigned tasks in accordance with contract specifications. Under the X-33 cooperative agreement, insights are gained through NASA technical personnel working alongside personnel from Lockheed Martin and other industrial partners. This ongoing involvement in the work enables NASA to obtain real-time and detailed insight into program activities.[34]

As the major funding partner, NASA agreed to supply its capital contributions in stages, payments varying from $8000 to $75 million, allocated on the completion of more than 160 milestones. Under the terms of the original agreement, NASA's contribution to the undertaking remained fixed. Lockheed was responsible for any cost growth that might occur during the development effort. Most importantly, Lockheed was also responsible for future investments. That of course was the whole purpose of the undertaking: to entice the industrial partner to produce a full-scale SSTO commercial launch vehicle.

As was typical for any undertaking of this sort, Lockheed executives put together a contributing team. It consisted of Lockheed for overall project management, Rocketdyne for engines, Rohr (also known as B. F. Goodrich Aerospace) for the thermal protection system, Allied Signal Aerospace for subsystems, the Sverdrup Corporation for ground support equipment, plus various NASA personnel. Project leaders kept the number of people working on the development effort deliberately small, both to conserve costs and to promote innovation. Lockheed ran the project through its "skunk works" operation in Palmdale, CA, which had a fifty-year tradition of conducting innovative projects through lean project teams.[35]

The partners agreed to producing a flight-ready X-33 within three years, by 1999. They would fly the test vehicle 15 times. For the most ambitious profile, the vehicle would take off from a vertical position at Edwards Air Force Base, climb to an altitude of 50 miles, and glide to a landing in Montana.[36] Based on the technology development program, Lockheed would finance and build the full-scale VentureStar.

Technology Challenges

To make the VentureStar plan work, the development team had to build and fly the X-33. To prepare the X-33, team members needed to solve a number of technology challenges. Program objectives called for a significant reduction in the amount of preparation time needed to prepare the vehicle for flight. NASA insisted that the new space vehicle be flown in an "aircraft type" mode, like a commercial airliner being prepared for another trip.[37] Maintenance actions needed to be "significantly reduced."[38] Technical objectives called for a ground crew numbering no more than 50 people, requiring the team to eliminate the elaborate space shuttle assembly process.[39] To do this, the X-33 development team needed to internalize the external fuel tanks, upgrade the main rocket engines, and replace the time-absorbing shuttle thermal protection tile system. These were the main technology challenges.

The engines inside the new vehicle had to do all the work of lifting the planned vehicle from a vertical position upward toward space. In the X-33, there were two. The fuel tanks had to be super-light and small enough to be incorporated inside the airframe of the vehicle. To manufacture the internal fuel tanks, the team planned to use composite materials. To cut more mass, the X-33 team removed the cockpit and all of the crew life-support systems. The X-33 and subsequent VentureStar would fly and land in an automated mode. If astronauts wanted to fly on the VentureStar, they could ride in the cargo bay.

A fully fueled space shuttle weighed roughly 4.4 million pounds sitting on the launch pad. The X-33—roughly half the size of the planned VentureStar—would weigh 285,000 lb.[40]

The technical history of the X-33 development effort is an often-told tale. For propulsion, the X-33 team planned to use a device known as a linear aerospike engine. The space shuttle utilized three bell-shaped engines on the orbiter and two powerful solid rocket boosters. Unlike a bell-shaped engine, which produces thrust on the inner walls of a combustion chamber, an aerospike engine produces thrust on the outside of a V-shaped ramp. This produces a curious effect. As the spacecraft gains altitude and air pressure falls, the shape of the combustion plume changes. In a bell-shaped engine, the nozzle shape is fixed, lessening the efficiency of the engine at nonoptimal altitudes. On an aerospike engine, one side of the combustion plume is open. The subsequent changes in the propulsion plume produce more thrust under a variety of conditions, which, joined with other advantages, increases the engine's performance.

Members of the X-33 team test fired linear aerospike engines extensively at NASA's Stennis Space Flight Center near Pearlington, MS. The tests began in 1998 and continued through the development effort. The engines performed well. Rocket engineers made plans to install them in the X-33 airframes being assembled at Palmdale, CA.

For their thermal protection system, the X-33 team planned to use a metallic super-alloy. The use of metal for heat deflection and aerodynamic pressure load support conjures an image of a spaceship wrapped in foil. In fact, the X-33 team used metal panels. Engineers planned to install metal panels on the bottom of each vehicle, placing the panels over fibrous insulation that was enclosed in foil. For control surfaces and the leading edge of the wings, the team used carbon-based composite materials. For the less exposed topside, the team planned to install insulation blankets like those placed on the leeward side of the space shuttle.[41]

Metal panels tend to flutter under the stress of reentry, a significant technical challenge. Members of the X-33 team tested the panels in heat and pressure chambers. The thermal protection technology performed well.[42]

That left the composite-based fuel tanks as the major remaining technical challenge. The process for constructing composite fuel tanks can roughly be compared to the process of constructing a fiberglass boat. Composite materials are overlaid and cured. Lightweight carbon fiber reinforced plastics are a good material.[43] For the large liquid hydrogen container, the process required the fabrication of 100-pound panels secured together with seals. The challenge involves finding the right sort of materials that after fabrication remain flexible when exposed to very cold fuel and do not break, especially along the joints, when fuel is expelled. Tanks also need to withstand the intrusion of plumbing and electronic devices. Traditionally, composite structures are cured in pressure chambers known as autoclaves.

Construction of the smaller liquid oxygen tanks went well, a consequence of the decision to forgo composite materials. The first oxygen tank arrived in Palmdale in early 1998.[44] Technicians fabricated it using aluminum, a less challenging material. For the larger hydrogen tanks, project workers planned to maintain the composite design. The hydrogen tanks resisted completion. At first, the cure cycle failed. Bubbles and cracks appeared. When filled with cryogenic fuel and subjected to structural loads, the tanks leaked. The outer skin and honeycomb center pulled away from the inner lining.[45] Hydrogen seeped into the core. A special investigation team blamed a flawed design.[46]

The X-33 team proposed a solution. Instead of composite materials, engineers proposed that the hydrogen tanks be made from an aluminum–lithium alloy, an older technology.[47]

Engine work was progressing; thermal panels were coming together. Vehicle assembly had begun at Palmdale. Project workers began fabricating aluminum–lithium hydrogen fuel tanks. An outside "red team" declared the basic approach to the X-33 to be sound. The first flight date slipped from the originally intended early 1999 in the original announcement to late 1999, to mid-2000 and then beyond as the new century began.[48] With it, project costs grew commensurately.

By early 2001, the original enthusiasm for the X-33 program expressed at the 1996 announcement had dissipated. The X-33 project was behind schedule. It needed more money. A series of failures had rocked NASA's overall low-cost initiatives. The House Science Committee held hearings on the program. A retired NASA chief engineer, much respected by the committee, criticized the decision to use aluminum–lithium fuel tanks, questioning the value of using an old technology if the purpose of the X-33 project was to innovate.[49] A new presidential administration came to town.

Assessing the Effort

On March 1, 2001, NASA and Lockheed officials agreed to terminate the X-33 program. More money might produce a flyable X-33, but that was not likely to result in a usable VentureStar. Discontinuation of the effort raised three questions:

1. Could the undertaking have produced a pair of launch-ready X-33 flight vehicles?
2. Was the effort a true partnership?
3. Was the business plan for building the full-scale VentureStar workable?

The technical problems that team members encountered with respect to the hydrogen fuel tank could have been overcome. NASA scientists and industry engineers continued to work on composite fuel-tank technologies: Thirteen years later, the Boeing Company presented NASA with a large composite cryotank that passed tests at the Marshall Space Center.[50] Advances in that regard progressed less rapidly than the project schedule for the X-33, but were not insurmountable. The partnership could have produced a workable X-33, though at a higher cost than initially planned.

As of 2001, the partners had allocated over $1.3 billion to the X-33, an estimated $1012 million from the government and $356 million more from Lockheed. Officials at the Lockheed Corporation declined to award additional funds from their own treasury. To complete the X-33, project officials would have had to compete for part of the $767 million in new government funding that NASA had set aside for development of a new space launch system.[51] Don't bother to apply, NASA officials told the team. Instead, the money—with more to follow—went to 22 contractors for what became a conventional multi-stage rocket design.

By comparison to the cost of the original space shuttle development effort, the funding necessary to complete the X-33 was not a large amount. In that respect, the partnership worked. It excited a small group of people to make substantial progress toward a flight vehicle that could demonstrate the technological improvements needed to construct a SSTO vehicle.

Yet was a partnership needed to accomplish this task? Stated another way, could the government have accomplished the same result through a conventional contract? The answer to this question lies in the financial arrangements for the program. Under the terms of the partnership, both parties contributed funds and—in that respect—both risked losing money if the project did not continue to completion as planned. Sharing risk and capital is a fundamental feature of a public/private partnership.

Analysis suggests that the government carried most of the financial burden and that the corporate partner risked very few invested funds. A General Accounting Office (GAO) study released in August 1999 estimated that the partners as of that season had contributed a sum total of $1.3 billion to the X-33 program. The government's cash contribution was fixed at $1012 million. Lockheed's cash contribution had risen from $212 million in 1996 to $287 million as of 1999; its additional contribution paid for delays and technical revisions, as prescribed in the original agreement. That seems like a substantial corporate share. The simple sums, however, mask particular features of the allotments that affected the real distribution of burden.

GAO analysts estimated that the government contributed an additional $113 million in personnel costs to the project, a result of NASA's willingness to contribute facilities and labor to the undertaking. That raised the total estimated government contribution to $1125 million. Of the industry share, the analysts continued, the commercial partner could charge some $161 million to overhead payments on other government projects. Federal procurement policy allowed industrial contractors to charge independent research and development outlays in this way. Absent a detailed audit, analysts could not tell whether Lockheed comptrollers took advantage of this policy. If they did, the effective industry share would fall from $287 to $126 million. The resulting distribution would thereby shift to $1286 million from the government and $126 million from industry.[52]

In that respect, the arrangement looked less like a partnership than a conventional government contract. Under the latter, the agent or contractor generally remains willing to work so long as the principal continues to spend money. When the flow of funding ceases, so does the project.

The reluctance of the corporate partner to invest more than 10% of the cost of the project raises an interesting question. Was the plan for an industry-financed VentureStar vehicle ever feasible? NASA officials canceled the X-33 project not so much because of its failure to produce a suborbital demonstrator, but because of the unlikely prospect that the industrial partner would use that knowledge to produce the VentureStar. While additional funds might have produced a flyable X-33, the probability of that investment producing an orbital vehicle was very small.[53]

Lockheed presented a VentureStar financial plan as part of its 1996 proposal. Its staff met periodically to discuss flight plans for the vehicle. It formed a limited liability corporation (LLC). Yet when confronted with the necessity of making additional investments to complete the X-33, the corporation declined.

Part of the company's reluctance arose from demand. When NASA officials set the financial goals for their first-generation space shuttle in 1971, they counted the number of shuttle-sized payloads launched between 1963 and 1971, extrapolated that experience into the future, and assumed that the shuttle would capture that market. During that period, the USA averaged 61 flights per year. The Soviet Union averaged 65 flights per year from 1965 to 1970.[54]

Likewise, various analysts projected the demand for launch services during the first decade of the twenty-first century when the VentureStar might fly. In 1998, a Federal Aviation Administration study predicted 56 commercial satellite launches per year for the twelve years following. If VentureStar could capture the bulk of that market, it stood a chance of becoming financially successful.

By 2001, those launch forecasts had fallen dramatically, however. The actual worldwide commercial launch market that year fell to half the projected demand. That left SSTO advocates with little more than a rosy scenario: the hope that a very low-cost, reusable vehicle would attract customers who would enter the market only if launch prices fell. A 2003 analysis by the ASCENT group dashed that idea. In a textbook case of price inelasticity, the report predicted that the demand for commercial launch services would rise less rapidly than launch prices might potentially fall. In practical terms, a low-cost VentureStar vehicle that reduced launch costs by a factor of five would generate only two and a half times more demand. "It doesn't take an MBA to realize that such an RLV [reusable launch vehicle] would generate less revenue than existing expendable vehicles," said one commentator, "making it very difficult to pay off the huge investment required to develop such a vehicle."[55]

Much speculation appeared regarding the exact shape of Lockheed's business plan for developing VentureStar. Lockheed executives did not promote the details contained in their original 1996 plan. Writing at the time of the contract award, an analyst for the Space Access Society reported that Lockheed planned to spend $2 billion from its own cash accounts "plus a bit more than that in short term loans" to build three VentureStars. The vehicles would be capable of carrying 15–30 tons to various orbits, the report said. As time passed, the estimates rose. A staff writer for the *Los Angeles Times* set the cost at $5 billion for two spacecraft. A journalist working for SpaceCast News Service reported that the VentureStar construction program would cost "in the range of $6 billion or more."[56] A 1999 GAO report said $7.2 billion for the production of two vehicles.[57]

Observers generally agreed that Lockheed planned to recover much of its initial investment by selling launch services to the US government. Again, speculation abounded. How much would the government pay? Would the government pay more than a commercial customer? The writer for Space Access announced that Lockheed would sell shuttle-type flights to NASA for near-shuttle-type prices.

To receive a decent return on its investment, Lockheed would need to sell 20–30 flights per year, a substantial share of the overall launch market. NASA's operational requirements for VentureStar set the launch price objective at $1000 per pound.[58] For a heavy 50,000 lb payload delivered to the lowest of low-Earth orbits, that would produce gross revenue of $50 million per flight.

The numbers simply did not compute. It is hard to make money running a low-cost transportation service that makes only 20–30 deliveries per year. To recover its investment, a space access corporation would need to spend hundreds of millions, not billions of dollars on vehicle development. Alternatively, it would need to charge someone much more than $1000 per pound. That someone would most likely be a government agency, providing support in forms such as subsidy payments or loan guarantees.[59]

Watchful observers learned a great deal from the X-33 experience. The first lesson confirms an observation already well established by that time: the federal government, working with its industry partners, is a capable innovator. The X-33 team could have built their demonstrators with an additional investment of funds. The X-33 could have flown, although with ultimate results that remain quite unknown since the suborbital flights never occurred.

Second, the public/private partnership proved to be a useful arrangement for holding down investment costs. Team members could have reached the first suborbital flight for a total investment less than one-tenth the scale of the $23 billion (1996 dollars) required to build and fly the first two space shuttle orbiters.

Commercialization was a different matter, however. Even had the partnership team produced a workable X-33, it is unlikely that Lockheed would have produced the VentureStar. The third lesson therein confirms experience from similar government undertakings. Public officials are not skilled at picking commercially successful technologies in advance of actual performance. The government is not a good venture capitalist. (Neither are private investors, one might add; the private market moves in ways that are often indiscernible in advance.) Government officials struggle to anticipate the direction in which future markets will move and they can only offer rough estimates regarding which ventures will attract sufficient customers to provide an adequate return on investment. In attempting to sort winners from losers, public officials are often motivated by factors that may bear only a tangential relationship to fiscal performance.

In this respect, cancelation of the X-33 development effort represented less a failure in technological innovation than a failure in business planning. As the technology effort progressed, corporate officials grew less confident of their ability to prevail commercially in a competitive launch market. The technology effort continued so long as the government funding did, but when the latter ended, so did the corporate plan.

In response, NASA officials adjusted their partnership arrangements for the next major joint launch vehicle undertaking. They continued to provide seed money for technology development, as they had done with the X-33. They maintained their role as an "anchor tenant" for new launch vehicles, promising to use the commercially developed rocket ships as a way of guaranteeing sales. They continued to solicit competing proposals from a variety of prospective firms. Additionally, they continued to defer the responsibility for vehicle production and flight operations to commercial firms.

Beyond those arrangements, NASA officials made one important change: they altered their efforts to pick winners in advance of actual performance. For the next round of launch partnerships, the government encouraged a number of commercial providers to test their designs in space and around the global marketplace.

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CHAPTER 12

Microgravity, Macro Investment: Overcoming International Space Station Utilization Challenges Through Managerial Innovation

Emily A. Margolis

In July 2015, the Pew Research Center published a report that compared the attitudes of the general public and members of the American Association for the Advancement of Science on various scientific issues. Of the topics surveyed, the subject groups were in greatest agreement on one issue: the International Space Station (ISS). The study revealed that 64% of the public and 68% of the scientists found the ISS to be a "good investment" for the United States.[1]

The ISS is certainly an investment. Between the start of the program in 1985 through 2013, the US government spent an estimated $75 billion on design, construction, program costs, and shuttle launches. NASA Office of the Inspector General projects that the cost of maintaining the station throughout the remainder of its operational life, which NASA recently extended to 2024, will exceed $4 billion per year.[2] The total

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monetary cost of the ISS is even greater when contributions from the European, Japanese, Canadian, and Russian space agencies are tallied.

However, what entails a "good investment" in the public consciousness? Is it as simple as a positive impact on the American economy? Is it less tangible, and perhaps only measurable in a nonquantitative manner?

From the beginning, NASA envisioned a tangible and wide-reaching impact for the ISS. In his 1992 address at the Space Station Freedom Utilization Conference, NASA Administrator Daniel S. Goldin promised an "enormous return on investment," one that would touch every human life. "The tidal wave of research that's waiting to be flown in space," he explained, "is what can let us live longer, in a cleaner environment, with a higher standard of living."[3] The station, it was hoped, would achieve these lofty goals through the advancement of basic and applied science, as well as technological development.[4]

Nearly two decades after the launch of the first station element in 1998, it is not obvious what value the ISS has added to the lives of the American people. The station's ability to deliver on Goldin's utopian vision was complicated by a mismatch between its mission and its management structure. The ISS is unique among NASA's scientific assets, as it was designed to serve three distinct communities of users: academic scientists, engineers, and industrialists. Each community evaluates, prioritizes, and funds research in different ways. The history of the management of the scientific utilization of the ISS exposes a constant negotiation between NASA's objectives, the expectations of its diverse user base, and federal pressure to commercialize the space station.

As early as 1993, some individuals at NASA realized that the plans for managing station research, which were largely modeled after the funding of basic science through grants, would not attract or satisfy engineers and industrialists. This realization motivated nearly fifteen years' worth of studies and inquiries into alternative managerial structures and culminated in 2011 with the installation of the Center for the Advancement of Science in Space (CASIS) as the sole entity responsible for the utilization of the US share of the station's scientific resources by nongovernmental users. This chapter explores the events and ideas that led to the formation of CASIS.

It is yet to be seen whether CASIS specifically, or a nonprofit organization (NPO) more generally, was a positive innovation. The ISS is a testing ground of sorts for the presumed causal relationship between managerial and scientific innovation. The success or failure of this project will have significant implications, not only for NASA specifically, but also for the fate of future long-term federally funded scientific assets and large-scale international scientific collaborations that aim to routinize the process of scientific discovery.

Dreaming of a Laboratory in Space

For nearly a century, science fiction enthusiasts and engineers across the globe have envisioned space stations. The historical allure of science in space can be traced back to the work of Hermann Oberth, an early twentieth-century German physicist and mathematician. Writing in the decade that American rocket pioneer Robert H. Goddard patented his multi-stage and liquid-fueled rockets, Oberth imagined repurposing rockets for scientific research once they reached orbit. Despite their differences, the myriad of station designs proposed since Oberth share a common feature: they are multi-purpose. Throughout history, space stations have been designed to function variously as outposts for human exploration and colonization of space, military installations, scientific laboratories, telecommunications facilities, observational stations, navigational aids, and tools for weather control.

The motivation that sustained NASA during the hard-fought political battle that brought the ISS to fruition stemmed from this long-held belief in wondrous possibilities in space. Like its predecessors, both real and imagined, the first permanently crewed American space station is multi-purposed, serving as a multi-disciplinary laboratory, manufacturing facility, and test habitat for long-range space exploration, as well as a tool of diplomacy and symbol of national prestige.[5]

The effort to create what would become the ISS began in the early 1980s. Following Skylab, the first US space station that orbited Earth between 1973 and 1979, some individuals at NASA pushed for a permanently crewed space station. One of those people was NASA Administrator James Beggs who, in May 1982, founded the Space Station Task Force. Beggs charged the Space Station Task Force with conducting preliminary studies and generating broad interest—at NASA centers, in industry, and abroad—for an international space station.[6] He understood the scientific and financial value to international partnerships. Not only would NASA be able to reduce costs and improve output by drawing on the scientific and technical expertise of other space programs, but collaboration also held the US government financially accountable to the project to a greater degree. Increasingly armed with the findings of the Space Station Task Force as well as station studies from Canada, Europe, and Japan, Beggs petitioned the White House for over two years before receiving approval for the station.[7]

In his State of the Union address on January 25, 1984, President Ronald Reagan mandated the building of a fully fledged space station. He announced the program in grandiose language:

> 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. A space station will permit quantum leaps in our research in science, communications, and in metals and lifesaving medicines which could be manufactured only in space. We want our friends to help us meet these challenges and share in their benefits. NASA will invite other countries to participate so we can strengthen peace, build prosperity, and expand freedom for all who share our goals.[8]

Reagan foregrounded the three primary functions of the station in his address: as a scientific laboratory that promised to host research capable of improving life on Earth, as a boon to the nation's economy, and as a diplomatic tool that demonstrated the possibility and value of international collaboration in space and on Earth, especially during the Cold War.

Three months after Reagan's address, NASA established the Space Station Program Office to coordinate the planning of the station, now named Freedom. Within a year, the Canadian Space Agency (CSA), European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA) signed bilateral Memoranda of Understanding with NASA that formalized their participation in the space station program.[9] The partners were obligated to make "substantial, significant, and well-defined" contributions to the station; yet the essential elements would be left to lead partner NASA.[10]

In the early years of station definition and design, NASA faced numerous challenges, outlined in historians John Madison and Howard McCurdy's article "Spending without Results: Lessons from the Space Station Program." Madison and McCurdy show how "budgetary politics, congressional micro-management, and technological risk" resulted in high expenditures without commensurate productivity. Due to rising costs and increasing delays, Congress required NASA to scale back the station design yearly between 1990 and 1993.[11] International partners were understandably frustrated by these numerous and unanticipated changes.[12]

In 1993, the USA invited Russia to join the space station partnership at the request of President William J. Clinton. Clinton was interested in engaging former Soviet scientists and engineers in a peaceful pursuit after the end of the Cold War. Additionally, NASA was interested in the practical knowledge and experience to be gained from experts who had worked on the Salyut and Mir stations for the Soviet Union space program. With Russia's Roscosmos onboard, Freedom was renamed the International Space Station.

Russia's addition was formalized with another series of bilateral Memoranda of Understanding in the summer of 1998, as well as an Intergovernmental Agreement among all of the partners.[13] That fall, orbital assembly of the station began.[14] Construction of the station would not be completed for another twelve years, however, because of production delays as well as the grounding of the space shuttle fleet following the loss of *Columbia* in February 2003. The ISS has been continually inhabited since October 2000 and science has been conducted aboard since this date.

Realities of Research in Orbit

The ISS has three designated laboratory modules, as well as a few hundred exterior test beds for research payloads.[15] Experiments are conducted in these labs, test beds, and other locations throughout the station. For example, not long after the first astronauts arrived on the station in late 2000, they performed a complex plasma experiment in the airlock of ISS.[16] In the first thirteen years of the station's operational life, approximately 1600 experiments were conducted on behalf of over 1800 principal investigators from 82 nations.[17] Disciplines represented include high-energy particle physics, geophysics, biology, molecular and cellular biotechnology, agriculture, human physiology, combustion, and materials science.[18]

The US laboratory Destiny was the first to be added to the station in February 2001 (Fig. 12.1). Like the ISS itself, Destiny is composed of modular units known as EXPRESS (EXpedite the PRocessing of

Fig. 12.1 NASA Astronaut James S. Voss working with the EXPRESS Racks on Destiny Module aboard the International Space Station in 2001. (NASA, image number iss002e5964, public domain (Available at https://images.nasa.gov/#/details-iss002e5964.html.))

Experiments to the Space Station) racks, designed at the Marshall Space Flight Center and constructed by the Boeing Corporation. Each rack can house numerous experiments that are environmentally and vibrationally isolated from one another. They run semi-autonomously and ISS crew members or the Payload Rack Officer at Marshall can monitor and control the racks. Destiny also includes the Microgravity Science Glovebox, a transparent sealed box with glove inserts that permits the crew to work with liquids, small particles, and hazardous material on board.[19] It also houses the Human Research Facility rack, which permits astronauts to collect specimens, perform ultrasounds, and measure, record, and transmit other biometric data.[20]

In 2008, the ESA laboratory Columbus and the JAXA laboratory Kibo were joined to the ISS in February and May, respectively. Columbus is approximately the same size as Destiny (4300 cubic feet) and also includes experiment racks, as well as four exterior test beds for conducting research in the harsh environment of space. Kibo is the largest of the laboratory modules. It includes six components: a pressurized module similar to the other laboratories, an exposed research facility, a logistics module, an exterior robotic arm, an interorbit communication system, and an airlock.[21]

It is worthwhile to consider the names of the laboratory modules, which reflect each partner's understanding of the significance of science in space. Destiny invokes the foundational American mythology of manifest destiny associated with the exploration of the western frontier. The name ties the space laboratory not only to America's past, but also to its present. It implies that space science is America's destiny, and therefore warrants full political and financial support. Columbus is named after the famed fifteenth-century Italian explorer, whose wayward journey led to Europe's first sustained contact with the New World. Columbus' voyage, sponsored by the Spanish crown, was made in the hopes of taking advantage of the spice trade. This association underscores the European view that science in space can open new worlds and new markets. Kibo, meaning "hope" in Japanese, indicates a generally optimistic view toward the possibility of space science. The simple name indicates faith in the yet unknown results of orbital research.

As per the Memoranda of Understanding and Intergovernmental Agreement, each space agency is responsible for designing, financing, constructing, and maintaining its own laboratory module. The User Operations Panel of the Multilateral Coordination Board, which includes representatives from each space agency, is responsible for overseeing utilization of the station resources and accommodations. According to Article 8.3 of the Memoranda of Understanding, NASA retains 97.7% of user accommodations on Destiny and its external test beds, as well as 46.7% of the accommodations on Columbus and Kibo. ESA and JAXA retain 51% of the accommodations on their own laboratories, and CSA has access to 2.3% of the accommodations on the three laboratory modules. Roscosmos is the sole user of all Russian research facilities on board. The Memoranda of Understanding permit the partners to "barter for, sell to one another or enter into other arrangements for any portion of their Space Station allocations."[22] Partners retain the intellectual property rights of their data.[23]

NASA Administrator Daniel Goldin envisioned a utilization scheme that reflected NASA's support for the commercialization effort that began in the 1980s. He intended for 30 percent of US user accommodations to be allocated for commercial research, NASA life science studies, and NASA microgravity experiments. The remaining 10 percent would be used for space and earth sciences research.[24]

Until 2011, NASA managed basic research on the station through a decentralized sponsorship program. Sponsoring offices, which included the Office for Space Science Applications, Office of Aeronautics and Space Technology, Office of Space Flight, and Office of Commercial Programs, were responsible for "perform[ing] outreach to their constituencies, develop[ing] mechanisms to select payloads for flight, advocat[ing] for their research needs within the agency, manag[ing] their research program, including payload development, integration and operations, and fund[ing] research."[25] Throughout the lifetime of the ISS, NASA has been restructured numerous times. As offices were formed and dissolved, the above functions were carried out by successor organizations, including the Office of Life and Microgravity Sciences and Applications, later reorganized as the Office of Biological and Physical Research in 2000.

Concurrently, industrial research was facilitated through two pathways. The first, known as an Entrepreneurial Offer, entailed self-initiated research proposals "for the purpose of creating value-added products or services for sale primarily to the private sector."[26] Entrepreneurial Offers merely granted access to the station. Industrialists were responsible for hardware development and payload integration, as well as the full cost of the research, including an initial $20.8 million fee, as well as additional costs relating to transportation, crew time, and on-board storage.[27] This expensive pathway to the microgravity environment was intended for research that promised short-term returns.

Basic research with the potential for long-term returns was supported through Commercial Space Center (CSC) partnerships. Founded in 1985 for the purpose of increasing "private sector interest and investment in using space for commercial activities," CSCs, then known as Centers for Commercial Development of Space, were part of a broader scheme of commercialization of federal research and development programs pursued during the Reagan Administration.[28] As the other chapters in this volume demonstrate, NASA has been involved in various commercial partnerships since its founding. Legal scholar Edythe Weeks argues that the commercialization and privatization of space flight first became national priorities during Reagan's presidency, as evidenced by a 1984 amendment to the National Aeronautics and Space Act of 1958,[29] which read: "Congress declares that the general welfare of the United

States requires that the Administration seek and encourage, to the maximum extent possible, the fullest commercial use of space."[30]

Mostly based out of universities, CSCs involved "teams of industry, university, and other non-NASA government organizations."[31] Each CSC "conceptualized, developed, and conducted" its own research program according to its area of focus, and facilitated hardware development and payload integration.[32] They were supported through small grants from NASA's Office of Commercial Programs, as well as funds from industrial and academic partners.[33] CSC partnerships took the form of sponsorships and consortium membership. Sponsors provided funding for specific research projects, while consortium members contributed a flat fee toward the experimental program.[34] Costs were as low as $10,000 and could be waived through in-kind contributions to the CSC.

From Dreams to Discontent

The sponsorship and CSC programs left much to be desired, and scientists, both academic and industrial, were not shy about expressing their grievances. Reputed scientific periodicals *Nature* and *Science* frequently published news stories and editorials that highlighted users' and potential users' discontent with the management of the ISS. The two biggest areas of concern for the scientific community, as represented by the readership of these professional journals, included the selection and funding of research.

The episode surrounding the Alpha Magnetic Spectrometer (AMS), one of the highest-profile experiments installed on the ISS (Fig. 12.2), encapsulates the concerns relating to the selection process. In May 1994, Goldin invited Samuel Ting, a Nobel Prize-winning physicist, to discuss Ting's latest experimental design.[35] The AMS, Ting explained, was designed to detect and measure particles and anti-particles after deflecting cosmic rays through powerful magnets.[36] Its purpose was to identify anti-matter and dark matter in hopes of understanding why the universe favors matter over anti-matter.[37] In order to access cosmic rays before they are absorbed in the Earth's atmosphere, it was necessary for the AMS to operate in space. Goldin was suitably impressed by the grand ambitions of Ting's instrument, and perhaps his accolades, and agreed to include the AMS on the ISS.

Many in the scientific community were displeased with Goldin's selection, mainly because of the unconventional way in which it was

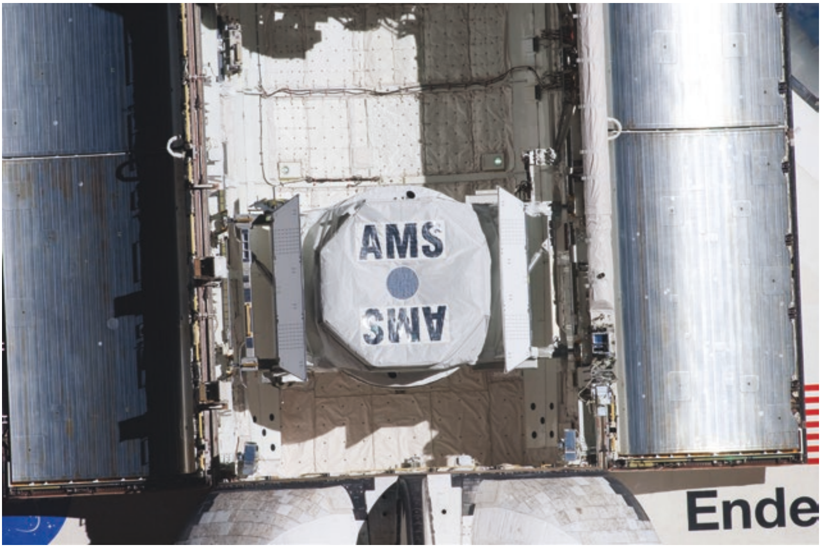

Fig. 12.2 View of the Alpha Magnetic Spectrometer in space shuttle Endeavour's payload bay. AMS was installed on the International Space Station by STS-134 in 2011. (NASA, image number ISS027-E-032216, public domain (Available at https://spaceflight.nasa.gov/gallery/images/shuttle/sts-134/html/iss027e032216.html.))

made. With the exception of the AMS, all other experiments had been solicited through a public call for proposals, which guaranteed equal opportunity for investigators to present their work to the selection committee. Additionally, AMS bypassed the peer-review process through which proposals were evaluated.[38] NASA often relied on the expert analysis of the National Academy of Sciences to generate "prioritized shopping lists" for selecting experimental proposals.[39] Such was not the case in this instance.

Goldin and NASA were heavily criticized for circumventing standard procedures. Because of the informal process by which the AMS was selected for flight, NASA's endorsement was not universally shared. Particle physicists felt that the AMS was outside the "mainstream" concerns of the discipline and that, even if successful, its results would not be of value to the community at large. Others, however, defended the experiment. John Ellis, physicist at the European Organization for Nuclear Research, excitedly claimed that "the AMS is by far and away the most important science currently planned for the space station."[40] It should be noted that the AMS was designed and tested at Ellis' institution. According to *Nature*'s Tony Reichardt, the Ting episode "shows both the fervent hope among the space station's builders that it will produce world-class scientific results," as well as "their desire for respect from the larger scientific community, which fears that it won't."[41]

Concerns over NASA's management of its orbiting laboratory continued beyond the selection of the AMS. In the late 1990s, scientists complained that NASA doctors flew biomedical experiments without peer review. Peer review is essential to the selection of basic science experiments, as it ensures the soundness of the proposal, as well as the relevance of the work. It makes sure that the limited funds available are awarded to projects with the greatest potential to make a real and significant contribution to the field. Because NASA was perceived as circumventing this important process, *Nature* reported that there was "broad agreement that much of the research planned for the station [was] likely to remain tangential to the central concerns of biomedicine and materials science."[42] The agitation over NASA's biomedical experiments reveals a general lack of understanding of the various pathways to the station. It was NASA's prerogative as the ISS operator to select in-house experiments and other federally sponsored research projects according to a different set of criteria than that applied to proposals from the wider scientific communities. The specific criticism is leveraged against the seemingly arbitrary selection process, rather than NASA's privileges as station operator.

This incident and others demonstrate that the selection process lacked transparency and consistency, which was a concern shared among academic and industrial scientists. In February 2002, Booz Allen Hamilton and Equals Three Communications, under NASA contract, produced a "Commercial Market Outreach Plan for the International Space Station." They conducted interviews with NASA and CSC staff, as well as representatives from potential industrial users of the ISS. The final plan reported that CSC researchers complained of the "apparent arbitrariness of the decisions regarding what payloads will be manifested and flown."[43] Even within NASA there was confusion over who or which office was responsible for "booking" commercial research on the station.[44] Booz Allen Hamilton and Equals Three Communications identified NASA's outreach and communications strategies as the primary source of this confusion. As late as 2010, Jeff Jonas, ISS researcher and Senior Vice President of Research and Development at Shire Pharmaceuticals, was still advocating a more transparent selection process open to a wider audience.[45]

The other primary concern of ISS users with basic science experiments was funding. Participating in station research is very expensive, and can be cost prohibitive. Consequently, some microgravity researchers have sought out ground-based alternatives, such as working with mutant breeds of the plant *Arabidopsis thaliana*, whose roots do not succumb to gravity.[46] In order to enable researchers in government, academia, and the commercial sector to conduct experiments on board the station, the Office of Life and Microgravity Sciences and Applications distributed grant money to defray the high cost of participation. Award recipients were not guaranteed funding, however.[47] As a federal institution NASA is ultimately responsible to Congress and the American taxpayers. Through the NASA Authorization Act, which is renewed every one to five years, Congress prioritizes funds and recommends activities to NASA.[48] When a project falls outside of the bounds of the recommendations of Congress, it can cease to exist. For example, in 2004 President George W. Bush announced his "Vision for Space Exploration," which charged NASA with returning Americans to the Moon and sending them to Mars and beyond. In accordance, Bush proclaimed that "we will focus our future research aboard the station on the long-term effects of space travel on human biology."[49] These mandates were reflected in the NASA Authorization Act of 2005, from which the agency took direction through 2010.

Louis Stodiek, ISS researcher, described the consequences of the "Vision for Space Exploration" in his testimony before the House Committee on Science, Space, and Technology in April 2008. "NASA's life and physical science programs were drastically cut," he explained, "with many lines of research being eliminated altogether."[50] Dr. G. Paul Nietzel offered a similarly glum testimony before the Senate Subcommittee on Space and Aeronautics hearing on "NASA's Space Shuttle and International Space Station Programs: Status and Issues" in July 2007. The Georgia Institute of Technology professor explained, "NASA sent letters to hundreds of investigators in the program, informing them of significant cuts in their funding for FY06 and the termination of their grants effective September 30, 2006."

He concluded that "the reestablishment of an external research community will take years, if it can be accomplished at all."[51]

Industrial researchers were less troubled by finances and more concerned with timing, which Booz Allen Hamilton and Equals Three Communications identified as a "critical barrier" to microgravity research.[52] Speedy and reliable access to the ISS is essential for commercial users. Historically, access to the station has been highly inconsistent, and the resulting delays served as financial disincentives to station research. Until 2008 when ESA's Automated Transfer Vehicle became operational, the station was only accessible by space shuttle and Russian *Soyuz* and *Progress* spacecraft. Following the tragic loss of space shuttle *Columbia* as it returned to Earth on February 1, 2003, NASA grounded its shuttle fleet for thirty months while the accident was investigated. During this time, the expendable *Progress* spacecraft were the only means of transporting supplies and experiments to the ISS. Specimens and other data could only be returned to earth inside the *Soyuz* spacecraft, which primarily functioned as a ferry for cosmonauts and astronauts. Each *Soyuz* can transport a mere 132 lb of cargo from the station.[53] When shuttle flights resumed on July 26, 2005, a more relaxed launch schedule was pursued, with only seven missions through 2008.[54] During five crucial years of station construction and utilization, access to the ISS was greatly limited. Not only did this delay the completion of the station, it also set back the scheduled installation and use of experimental apparatus, as well as the return of specimens and data. Booz Allen Hamilton and Equals Three Communications survey respondents revealed special concern over the lack of "recourse for companies or individuals who may incur losses due to delays … on NASA's part." (Fig. 12.3).[55]

Another Way Forward

Long before the first experiments were performed in orbit, some at NASA recognized the significant challenges to ISS utilization posed by the diverse needs of the station's users. The history of the search for an alternative management structure can be broken into three distinct phases. First, recognition of the problem and early reconnaissance characterized the effort between 1993 and 1995. Second, a period of high interest in managerial innovation marked the years between 1998 and 2004, in which numerous internal and external studies on the subject

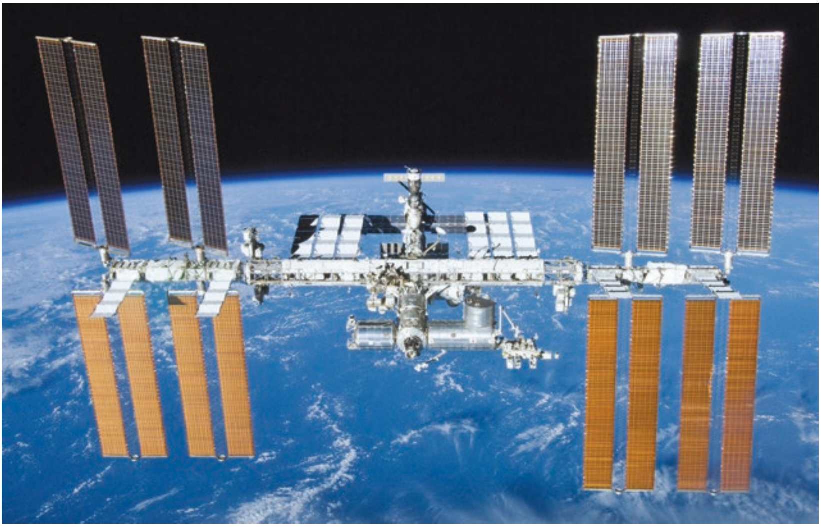

Fig. 12.3 The International Space Station viewed from space shuttle *Atlantis*, 2010. (NASA, image number S132E012208, public domain (Available at https://spaceflight.nasa.gov/gallery/images/shuttle/sts-132/html/s132e012208.html.))

were commissioned. Third, activity between 2004 and 2011 is defined by the "Vision for Space Exploration" and its aftermath.

Phase 1: Recognition and Reconnaissance

As early as the 1980s there was concern, both inside and outside of NASA, about the management of space station utilization. As McCurdy has shown, the fact that NASA was tethered to the political cycle has had a significant impact on the form and function of the space station. Throughout the design and development process, it became clear that "external organizations could be more effective at selecting and managing basic and applied research than a government agency subject to policy dynamics across changing administrations."[56] Free from the notorious bureaucracy of the federal government, an external entity could offer greater flexibility and stability to the management of this significant scientific asset.

Since 1982, the Space Studies Board of the National Research Council, which has served NASA in an advisory capacity since the agency's founding, has communicated its concerns over space station management in its correspondence to the NASA Administrator.[57] These concerns became louder and more frequent as the first station design was finalized. On February 25, 1994 the members of the Space Studies Board wrote to Goldin to express concern over the negative impact of NASA's "lack of familiarity" with the needs of the station's future scientific users for its planned utilization.[58]

That same year, Dr. Harry C. Holloway initiated the first investigation into managerial alternatives. Holloway, a doctor from the School of Medicine at the Uniformed Services University of the Health Sciences who was temporarily assigned to NASA, served as the first Associate Administrator of the Office of Life and Microgravity Sciences and Applications between 1993 and 1996.[59] In this role he was responsible for the utilization of the scientific resources aboard the space station Freedom. As he worked to facilitate basic and applied research in fields as diverse as biology, biotechnology, combustion, fluid physics, materials science, and occupational and aerospace medicine, Holloway recognized the difficulty posed by the diverse practices and customs of the space station user base.[60] Holloway envisioned a new approach to managing research at NASA field sites, as well as on the space station: a system of discipline-specific NPOs (nonprofit organizations). Drawing from his experience in the medical profession, Holloway wanted to follow a "distributed National Institutes of Health" model.[61]

He charged Mark L. Uhran, a recent NASA hire who had worked on the technical specifications of the space station since its inception as an engineer at Wyle Laboratories, with investigating alternative management structures. Uhran, who was assisted by a small committee, undertook a survey of managerial practices at organizations in academia and the public and private sectors that were identified as potential users of the space station. The purpose of the survey was to "evolve the institute concept into a broader concept that could handle science, technology, and commerce."[62]

Uhran began his survey with NASA's greatest scientific asset then in operation, the Hubble Space Telescope. Launched in 1990, Hubble allowed astronomers to observe space from low-Earth orbit across a wide range of the electromagnetic spectrum. Hubble was a natural subject for study, as it shared many characteristics with the space station: it was an expensive international collaboration designed and constructed over a period of decades. As Hubble was being planned in the early 1970s, questions arose about the scientific management of the telescope, especially as a result of the widespread feeling among potential users that NASA was “unresponsive… to scientific needs.”[63] A debate ensued over the proper balance of operator and user needs, which Robert Smith details in his 1993 book *The Space Telescope: NASA, Science, Technology, and Politics*. By 1981 the Space Telescope Science Institute was named as the Hubble science operations center. The Space Telescope Science Institute is operated by a consortium of educational institutions and NPOs known as the Association of Universities for Research in Astronomy.

Uhran interviewed the head of the Space Telescope Science Institute to learn not only about its structure and operation, but also about the process by which NASA was convinced to proceed with this model. As Smith notes, since its inception the space agency has not been keen to relinquish full or partial control of its projects to outside entities.[64] In fact, Uhran cites this culture of reluctance as one of the primary hurdles to pursuing managerial innovation for space station utilization.[65]

The Space Telescope Science Institute was not the perfect model, however, as Hubble and the space station differed in a key way: user diversity. Whereas Hubble is used for basic astronomical research, the space station was designed to accommodate basic research, technological development, and commercial applications. Uhran and his team aimed to learn about managerial practices from each of the three communities of potential space station users. They thusly looked to national laboratories, including the Department of Energy laboratories, as well as private corporations, such as Bell Laboratories, and private research institutes, including Woods Hole Oceanographic Institute and the Semiconductor Research Center.[66]

Uhran and his team’s preliminary findings were published in 1995 as “An Orbital Research Institute for Science and Technology.”[67] The report was widely disseminated within NASA and among potential station users and stakeholders. Feedback was solicited across a variety of platforms, including at advisory committee and leadership meetings, in briefings to the White House and Congress, at the American Institute of Aeronautics and Astronautics annual meeting, and at the International Forum for Scientific Uses of the Space Station.[68]

As Uhran describes it, the NPO plan was "controversial from day one," precisely because of NASA's reluctance to give up control.[69] Despite the detractors, there were also influential supporters within NASA, including Arnauld Nicogossian, who succeeded Holloway as Associate Administrator of the Office of Life and Microgravity Sciences and Applications in 1996.[70] During his tenure, Nicogossian took steps to implement the recommendations in Uhran's report.

Phase 2: A New Management Form

In 1998, interest in management alternatives for the scientific utilization of the space station within NASA grew beyond the Office of Life and Microgravity Sciences and Applications. In January of that year, NASA veteran Joseph H. Rothenberg was appointed Associate Administrator of the Office of Space Flight, which was responsible for the development and operation of the space station. After a career at Grumman Aerospace Corporation and Computer Technology Associates, Rothenberg joined NASA in 1983 as Hubble Operations Manager. From 1990 to 1994 he served as Associate Administrator of Hubble Flight Projects.[71] Perhaps because of his experience with Hubble and his familiarity with the Space Telescope Science Institute, Rothenberg was a strong advocate for an NPO approach to managing space station research. His support united the station operators (Office of Space Flight) and users (Office of Life and Microgravity Sciences and Applications) in a quest for an innovative managerial solution.

Within his first year as head of the Office of Space Flight, Rothenberg commissioned a joint study with the Office of Life and Microgravity Sciences and Applications of a reference model for "A Non-Governmental Organization for Space Station Utilization Management." In a letter accompanying the report, Rothenberg and Nicogossian expressed a desire to "initiate a discussion of a new management approach to R&D in low-earth orbit." They hoped to utilize a nongovernmental organization "for accomplishing an aggressive science, technology, and commercial development program while simultaneously limiting government functions to policy and oversight."[72] The timing of this report not only suggests Rothenberg's enthusiasm for the NPO concept, but also that the question of management was becoming ever more pressing as the launch of the first station element neared.

Momentum for the NPO concept grew alongside NASA's desire to exploit the commercial possibilities of the station. The 1998 Commercial Space Act strengthened NASA's commitment to the commercialization of the ISS, stating "a priority goal of constructing the International Space Station is the economic development of Earth orbital space" and that in "operating, servicing, allocating the use of, and adding capabilities to the space station," free market principles should prevail. In November of that year, Rothenberg and Nicogossian issued the "Commercial Development Plan for the International Space Station." This document outlined a strategy for engaging the private sector in both station research and operation. One of the four primary strategies was the establishment of a nongovernmental organization "to manage US utilization of the space station and to reduce cost/schedule impediments at the user–operator interface" by 2000.[73]

Between 1999 and 2000, three additional studies were conducted. Nicogossian first solicited input from the Space Studies Board. The National Research Council task group, under the leadership of Cornelius J. Pings, published its findings as "Institutional Arrangements for Space Station Research." The study reiterated a need for an NPO-type institution for effective and efficient management of station research, citing two advantages over in-house management. First, it would allow NASA to "keep its attention focused on cutting-edge R&D" rather than on the operational management of a long-term asset. This, the task group argued, was especially important at a time of shrinking budgets and federal workforce. Second, it would allow NASA to "bring the research community close to the operation," thereby fostering a better working relationship between station users and operators.[74] The NPO was thus a solution to two of NASA's perennial problems: limited resources and strained relations with the scientific community.

Following the release of the National Research Council report in 1999, NASA contracted Swales Aerospace and Computer Sciences Corporation to study the feasibility and possible form of an NPO to manage space station utilization. The Computer Sciences Corporation report, titled "ISS Operations Architecture Study" and published in August 2000, was based on interviews with staff at NASA Headquarters, the Johnson Space Center, the Kennedy Space Center, and the Marshall Space Flight Center. Computer Sciences Corporation proposed a

> Space Station Utilization and Research Institute (SSURI) to be procured through a new ISS [Program Office] contract. The SSURI, in turn, [would establish] a single top-to-bottom Utilization Operations function that, subject to contract limitations, performs the U.S. research and selection processes, manages the research interface to the ISS program, communicates the benefits of ISS research, and implements Utilization Operations services for the program.[75]

On the heels of these studies, Congress directed the space agency to implement an NPO to manage the station in the NASA Authorization Act of 2000. In response, NASA's Office of Space Flight and Office of Biological and Physical Research conducted an internal study to understand the potential impact of an NPO.[76] Input was solicited from ten offices, dispersed across NASA Headquarters, Johnson, Kennedy, Marshall, the Goddard Space Flight Center, and the Ames Research Center, that would be most directly impacted by this managerial change. Each group voted on the role an NPO should play in twenty different managerial tasks. The study suggested issuing a Request for Proposals for an NPO in October 2001, with implementation within five years.[77]

In 2002, NASA assessed the findings and recommendations of seven years' worth of studies in a report titled "International Space Station Utilization Management Concept Development Study."[78] Of the ten business models evaluated, it determined that the NPO offered the best possibility of success. The recommended plan was closely modeled after the Space Telescope Science Institute and was based on the practices associated with academic grants, even though many of the space station's users came from the commercial sector.[79] In September 2003, NASA issued a Statement of Work for an ISS NPO for public comment.[80] Five months later, the "Vision for Space Exploration" was issued and plans for the NPO were abruptly canceled.[81]

Phase 3: Establishing CASIS

NASA experienced significant organizational and programmatic changes in the aftermath of the "Vision for Space Exploration." In addition to the cancelation of the NPO, experiments that did not conform to NASA's new mission were defunded. The Space Station Program Office, located at the Johnson Space Center, was poised for financial hardship. Senator Kay Bailey Hutchinson (R-TX) envisioned a way to support her state's economy, as well as the basic research slated for the chopping block. She advocated designating the Destiny module of the ISS as a US National Laboratory, explaining that as such it would be "empowered to bring other, non-NASA, resources to bear in operating the ISS, thus freeing NASA of much of that operational responsibility, while at the same time allowing it to support the specific research it needs for the vision for exploration."[82] Hutchinson successfully included such a provision in the NASA Authorization Act of 2005. This legislation required NASA to submit a plan for the management of the National Laboratory within a year.

NASA responded with its plan in May 2007. The report to Congress described NASA's efforts, since the Authorization Act of 2005, to engage other federal agencies in ISS research. It indicated that these interagency partnerships, beginning with the National Institute of Health, shaped official thinking on the National Laboratory management structure. The report emphasized that the organization must be flexible and reflect the needs of the end-users. It recommended a phased implementation process, in which NASA control would be handed to the NPO in stages.[83]

In 2008, Uhran, who was now Director of the ISS, learned that the Boeing Corporation, primary contractor for the space station, had commissioned a study on maximizing scientific utilization from ProOrbis, a strategy and management consulting firm. ProOrbis maintains that "innovation is as important in management as it is in science or technology" and offered an innovative solution to the problem of station utilization.[84] Because of the proprietary nature of the study, NASA contracted ProOrbis for a similar report, which was delivered as "Reference Model for the International Space Station U.S. National Laboratory" in 2010.

The ProOrbis reference model emphasized a "research pathways completion" approach, described thus:

> Research pathways are the key to valuing fundamental science. They put R&D projects in their "value context" and help to establish what we know, what we don't know and what it might be worth to know it. In this way, they provide the strategic frame for both building a more robust underpinning for applied research and the relevancy for basic research. Articulating what value could be derived from a discovery and formulating a pathway to that value creates the opportunity for more targeted investment than shortening the cycle time between discovery and practical application.

> Improving national returns on R&D investments and articulating the value created could lead to dramatic increases in funding for basic research and more efficient use of funds available.[85]

This model was premised on the assumption that the research needs of the diverse users are not distinct, but fall on a continuous spectrum from basic to applied science. This fundamental assumption distinguished the ProOrbis model from the other NPO models that NASA and its contractors explored in the preceding decade.

In October 2010, NASA posted the "ISS National Laboratory Reference Model" online for public review, which drew heavily on the ProOrbis reference model. In December, NASA hosted a Public Day at its headquarters in Washington, DC, where interested parties could comment on the reference model, as well as express any confusion or concerns. In February 2011, it released a Cooperative Agreement Notice to solicit applications from prospective organizations. The application process was quite detailed, and included hypothetical case studies that revealed how the organization planned to prioritize research, respond to unexpected circumstances, and communicate with end-users.[86]

On July 13, 2011, NASA announced that the NPO known as the Center for Advancement of Science in Space would oversee the scientific utilization of the ISS US National Laboratory.[87] CASIS, sponsored by Space Florida, an organization dedicated to promoting the state's aerospace economy, is "charged with developing and managing a varied research and development portfolio based on U.S. national needs for basic and applied research; establishing a marketplace to facilitate matching research pathways with qualified funding sources; and stimulating interest in using the national lab for research and technology demonstrations and as a platform for science, technology, engineering, and mathematics education."[88] To fulfill these responsibilities, CASIS receives $15 million from NASA yearly, as well as half of the available cargo room on spacecraft traveling to and from the ISS.[89] NASA works closely with CASIS, providing technical expertise in addition to an official liaison.

Since becoming operational, CASIS has worked to engage a diverse community of end-users, including federal agencies, universities, and private companies. It evaluated 206 experimental proposals and awarded $20 million in grant money to 77 research teams through the start of 2015.[90] With the increasing commercialization of the ISS, from NanoRacks' experimental facilities to better access to the station courtesy of Space X and Orbital System's delivery vehicles, it looks like things are moving in the right direction.

Much remains to be seen, however. As early as February 2012, Senator Sherrod Brown (D-OH) wrote to Uhran to express his frustration with CASIS. "It is the general impression of the situation that CASIS is neither performing this type of work [creating research pathways], nor actively heading toward being able to perform this type of work," Brown explained. "Because of the limited life of the ISS, it may be time to consider a switch in leadership for this activity."[91] Brown was writing on behalf of his constituents affiliated with Space Laboratory Associates, which failed to secure the NPO cooperative agreement. Nevertheless, from the beginning CASIS was besieged with high expectations and pressure from NASA and Congress, as inaugural director Dr. Jeanne L. Becker outlined in her resignation letter of February 29, 2012.[92]

Conclusion

The dream of an orbiting laboratory was a long time in the making. It was seventy-five years after Oberth articulated his idea for a laboratory in space that the first component of the ISS was placed in orbit. While enthusiasm for space-based science research has not waned, the reality of the challenges has turned what was once a promise into a compromise. Perhaps CASIS can reverse this trend; NASA certainly hopes so (Fig. 12.4).

In light of the NPO saga outlined in this chapter, how can we understand the "good investment" results of the Pew survey discussed in the introduction? First, the scientific community's positive assessment of the ISS, despite the heavy criticism it leveraged at NASA, suggests that belief in wondrous possibilities in space is as strong as ever. Second, public perceptions of the ISS are equally optimistic because NASA's powerful public relations apparatus has shifted expectations for return on investment from the tangible to the intangible. ISS astronauts regularly engage with the public through social media, creating the perception that knowledge is being creating at all times in low-Earth orbit. Congress, however, wants a quantifiable return on investment, and NASA believed that managerial innovation was the best way to deliver on its promise.

The question of whether CASIS, or the NPO model more generally, was an appropriate solution to these utilization challenges remains to be answered. The answer will have important consequences not only for

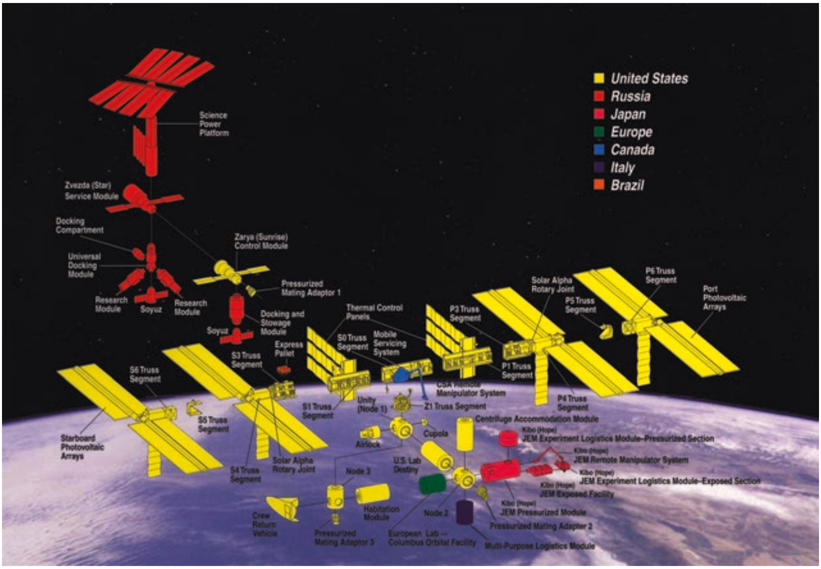

Fig. 12.4 Schematic of the International Space Station indicating contributions from partner nations, 1999. (NASA, image number MSFC-0201666, public domain (Available at https://mix.msfc.nasa.gov/abstracts.php?p=2414.))

NASA, but also for future large-scale, federally funded scientific assets. The answer will determine whether it is possible, or advisable, for governmental entities to attempt to serve a diverse user base representing science, technology, and industry. If successful, CASIS will demonstrate the importance of moving beyond a research model tailored to basic science in an increasingly commercialized space program. It will also suggest that NASA may not be the best entity to manage its long-term scientific assets.

Two lessons can be gleaned from this study, which echo the findings reported throughout this volume. First, managerial innovation is born out of necessity. Only because of concerns over the ability to meet the needs and wants of the diverse user base did NASA begin serious investigation into alternative managerial structures. Second, NASA is often hesitant to accept managerial innovation, in this case specifically because of its desire to retain control of the scientific utilization of the ISS. This proverbial "dragging of feet" may very well prevent the space station from being able to make a return on the American taxpayers' substantial investment.

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CHAPTER 13

NASA, Industry, and the Commercial Crew Development Program: The Politics of Partnership

W. Henry Lambright

On May 22, 2012, at 3:44 a.m., a Falcon 9 rocket owned by an upstart new aerospace company called SpaceX blasted off from Cape Canaveral carrying an unmanned spacecraft known as Dragon (Fig. 13.1).[1] There had been one postponement after another, and the launch was years behind schedule, but on this morning all went well. "Falcon flew perfectly!!" Elon Musk, SpaceX's leader, declared jubilantly on Twitter. "Feels like a giant weight just came off my back."

"It's a great day for America. It's a great day for the world," the NASA Administrator, Charles Bolden, told reporters. "There were people who thought that [NASA] had gone away. But today says, no we've not gone away at all. We've got the SpaceX-NASA team, and they came through this morning with flying colors." Bolden's predecessor, Michael Griffin, initiator of the program that led to this moment, stated: "This

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Fig. 13.1 Falcon 9 is a two-stage medium-lift range launch system. Created by SpaceX, Falcon 9 was intended to carry payloads to low-Earth and geosynchronous orbit. For its second launch In December 2010, the first Space X Dragon spacecraft was carried atop the launch system. (SpaceX, public domain.) (Available at http://www.spacex.com/news/2013/10/14/upgraded-falcon-9-mission-overview)

morning we witnessed a landmark accomplishment in spaceflight: the successful launch of the first privately developed cargo delivery vehicle."[2]

A few days later, Falcon 9 completed its journey to the International Space Station (ISS). Its success, emulated in 2013 by the Orbital Space Corporation, was the culmination of NASA's Commercial Orbital Transportation Services (COTS) program. Designed in 2005, COTS' success gave credibility to a much larger and more complex effort to carry astronauts to ISS, the Commercial Crew Development (CCDev) program. If private firms could deliver cargo, then they could transport crew. At that point, vital tasks performed by the space shuttle, retired in 2011, would have been replaced.

CCDev vehicles were due to be certified as operational in 2017, although many observers expected delays. When that event occurred, NASA would have achieved a major change in human spaceflight. This would not be so much a technological as a policy innovation. To the extent companies performed the cargo and crew transport tasks in low-Earth orbit (LEO), it would mark a change in the public/private division of labor in space. NASA would be able to devote more of its resources to deep space exploration.

Approach

Policy innovation occurs in stages: (1) agenda-setting, when an issue emerges for government decision, often triggered by an event or influential person; (2) formulation, when options for responses to that issue are forged; (3) adoption, when authoritative decision-makers choose a particular response and turn it into a formal policy; (4) early implementation, when decision-makers organize a program and provide it with resources to carry out the policy; (5) evaluation/reorientation, when decision-makers determine either to maintain or alter significantly an ongoing program based on initial results or a shift in political environment; and (6) later implementation to institutionalization, when an organization carries the program forward to its conclusion, and an innovation is incorporated into operational routines.[3]

Policy innovation can embrace technological and institutional change. It is a composite of innovations embodied in a "program." The process as a whole (and in its parts) is not autonomous. Technology does not move itself, especially when developing a technology costs hundreds of millions, in fact billions of dollars. Social scientists have theorized that fully understanding how technological innovation takes place requires seeing technology as socially constructed. When the technology involves government, the social construction becomes politically constructed. That is, different actors holding conflicting perspectives seek to influence policy to make an innovation move from inception to institutionalization, while others seek to hold it back. Actors try to influence policy and hence technological and institutional design.

For a program like CCDev, actors such as the President and the various staff offices of the White House are involved in decision-making. So also are Congress, industry, and other interested parties. Alliances for and against innovations form. Some are stronger than others. There are few monolithic institutions. To the extent that any one institution undertakes to advance (or at least influence) the process of innovation in space policy, it is NASA. However, NASA is not a monolith any more than the White House or Congress. Moreover, its political masters in the White House and Congress change with elections. So also do the NASA political executives appointed and confirmed to "run" the agency. What one NASA administrator wants in a program a successor may not.

What makes commercial cargo and crew policies particularly interesting is that they entail institutional innovations. These programs illuminate the dynamics of public/private partnerships. There have always been public/private partnerships in space. Typically, government is the customer and industry is the seller. Control is vested contractually in government. In COTS and CCDev, however, the government seeks to make industry a co-developer. More control of the relationship vests with industry than in traditional government–contractor arrangements. With more control, however, there is more responsibility for funding expected of industry. How much is enough private investment for a partnership to be seen as "commercial" to the parties involved? That can vary, and the term "commercial" is controversial.

Views about this institutional innovation in partnerships differ. Some in government favor a certain legal regime and others do not. There are many perspectives in the political construction process. Some actors in government want to restrict risk-taking by industry partners, while others trust companies to take necessary precautions, especially in the commercial crew field. This conflict is seen within NASA and Congress, as well as with others.

Industry is also not monolithic when it comes to the new partnership design. Companies accustomed to the old methods (and contract incentives) favor traditional cost-plus contracts in a partnership. However, new and smaller companies find the requirement of the old partnership burdensome. For them to innovate technically, they say they need greater freedom in making decisions about technical design, setting milestones, and payment schedules. As there is conflict within government, so there is conflict within industry. The social construct of technology cannot be separated from the politics surrounding the new public/private partnerships, especially those of CCDev. Partnerships cost money, and Congress especially cares about the division of payments. Congress cares also about whether money for commercial space takes funds from programs to which it gives higher priority, particularly in human space flight.

Advocates for innovating in technology and institutional arrangements try to build support for policies they favor. In the case of a major innovation, such as in cargo and crew transport, the process of change can take a lengthy period, a decade or more, and require a sequence of advocates pushing it from one stage to the next. Inevitably, many innovations are terminated short of being institutionalized. When an innovation is fully institutionalized, it usually reflects alterations from the original concept that are the price of acceptance by those with the most power over decision-making. The technological innovation may be dampened, along with some of the original institutional partnership concepts.

Given the political dynamics, the process does not necessarily follow the incremental-rational steps described at the onset of this section. Decision-making gets muddled. Where COTS and CCDev are concerned, we have two government–industry programs that overlapped. As COTS was implemented, CCDev was begun. Subsequently, one program influenced the other. COTS was ended (i.e., institutionalized). CCDev is still underway at the time of writing, but can be said to be in later implementation. It is likely to be institutionalized under Obama's successor, assuming continuing technical progress.

Agenda-Setting

Awareness of the need for a shuttle successor went back virtually to the beginning of the shuttle program in 1972. There were programs such as the National Aero-Space Plane (NASP), X-33/VentureStar, and others that government initiated but never fully implemented.[4] When Sean O'Keefe became NASA Administrator in 2001, his initial intent was to extend the shuttle to 2020 and develop a smaller complement, the Orbital Space Plane, to help carry astronauts and lighter cargo. That plan fell off the NASA agenda after the shuttle *Columbia* accident of 2003.

In the wake of that accident, which took the lives of seven astronauts, President Bush decided in his Vision for Space Exploration (VSE) to retire the shuttle in 2010, when building of the International Space Station (ISS) was complete. The USA would return to the Moon and build a hardware system called Constellation with multiple components, some of which could replace the shuttle, but which also could lead to the Moon, Mars, and beyond. The VSE contained words providing room for the private sector to play a role in space transportation. A presidential advisory panel on VSE implementation enlarged the commercial role. O'Keefe and Craig Steidle, whom he hired as his Associate Administrator for Exploration, discussed the possibility that Constellation, a government program, be the focus of the exploration mission, but that "repetitive" trips to service ISS might be spun off to the private sector.[5]

Steidle reached out for ideas about how to do this LEO mission in the post-shuttle era. He received suggestions from many sources, especially NASA's Ames Research Center, in the Silicon Valley region of California, which was studying various ways for NASA to partner with industry.[6] He also spoke with a number of new entrants to aerospace, smaller companies that wanted to compete for contracts.

Lessons learned from previous shuttle successor programs were gleaned. Perhaps the one that engaged most NASA veterans was the recent X-33/VentureStar program, which cost NASA and its partner, Lockheed, well over $1 billion in the 1990s before being terminated at the outset of the Bush Administration. (This program is featured in Chap. 11.)

There were differing views about X-33/VentureStar. Some NASA officials thought it would have succeeded with more money and political will. Others saw failure as inevitable due to technological overreach, the quest for a single-stage-to-orbit spacecraft. Still others drew lessons about the NASA–Lockheed partnership, saying that NASA was too dependent on one company, and competition would have given the agency more leeway in decision-making.

With White House encouragement, O'Keefe and Steidle initiated a modest effort to demonstrate private approaches to service ISS. Once ISS was fully assembled, a large and technically complex spaceship such as the shuttle would no longer be necessary. O'Keefe left NASA in early 2005 and Steidle departed not long thereafter, when a new administrator arrived. The idea of commercial cargo and crew was on the NASA agenda, but had not moved very far.

Formulation

In April 2005, Michael Griffin took NASA's helm. He was briefed on what had been conceived under O'Keefe in regard to commercial space. However, he had come to NASA with his own ideas about commercial space. He saw how a new private system could serve ISS, but he also wanted to use NASA to get more competition in aerospace (through new entrants) and thus lower costs to government. He wanted companies to put "skin in the game" along with the government. NASA would be an anchor customer and help them get started via services to ISS.[7]

Griffin talked to NASA lawyers, who explained that the agency had authority in its Space Act to stimulate new industry (it obviously had done that with communication satellites in the 1960s). The point was that this industrial policy had to be one step removed from traditional contracts. For work specific to NASA needs, the agency had to use Federal Acquisition Regulation (FAR) contracts. This system required much government oversight and government-controlled designs. Government paid all costs for development and often an additional fixed fee. Under the Space Act, companies would make the basic design decisions, take greater financial risks, and own the resulting hardware.

Following conversations with the White House Office of Management and Budget (OMB) and others, Griffin decided to "bet" $500 million on a commercial space program. It was an arbitrary figure he derived mainly from a previous position he had heading In-Q-Tel, an organization the Central Intelligence Agency had set up to engage innovative private firms with government acting as a "venture capitalist." Griffin wanted NASA to be a venture capitalist, serving the larger economy and NASA needs.

Griffin and his associates formulated what he called the Commercial Orbital Transportation Services program in the first few months of his tenure. He decided to place the new program (which absorbed the nascent effort that O'Keefe and Steidle had begun) at the Johnson Space Center (JSC). He chose JSC over Ames because he believed JSC would never accept a commercial cargo program, much less one involving crew activity, that it did not control.[8] However, Griffin also wanted the program to have a measure of autonomy, especially in its development period. He chose Alan Lindenmoyer of JSC as its director. This was done on the advice of Griffin's Associate Administrator for Space Operations, Bill Gerstenmaier, who stressed Lindenmoyer's capacity to "to think outside the box." Gerstenmaier represented NASA-user interests.[9]

COTS' broad goal was to develop a capability the USA and NASA could utilize. Griffin said he would protect the $500 million over his four-year tenure. Once the capability was developed, operations would follow under FAR requirements. NASA would shift from development to use. Companies would service ISS under a Commercial Resupply Services (CRS) program. This would entail billions over ISS' duration. Griffin believed companies would risk their own money in COTS to get the benefits of CRS.

Griffin informally gained approval for COTS from the White House and Congress, and on June 21, 2005, announced the proposed activity at a meeting of the Space Transportation Association. Griffin made it clear that COTS was a secondary program, a side bet that might not work. He was pursuing a government-owned rocket and spacecraft (Ares 1/Orion) as his priority. This was part of the revamped Constellation he was pursuing.[10] In September, he announced his Constellation design. There would be four elements: Ares 1, a rocket capable of taking a crewed spacecraft to ISS and beyond; Orion, the crew exploration spacecraft; Ares 5, a giant rocket that could take major cargo as well as people to the Moon and eventually Mars; and Altair, a Moon lander.[11] Ares 1/Orion would assure US access to LEO if the COTS program failed. Griffin said he preferred to have commercial companies for LEO and retain Constellation for deep space, but he could not risk reliance on an "experiment."

Adoption

On December 30, President Bush signed the NASA Authorization Act of 2005. That legislation formally adopted COTS. It directed the NASA administrator to "work closely with the private sector, including by—(i) encouraging the work of entrepreneurs who are seeking to develop new means to launch satellites, crew or cargo; (ii) contracting with the private sector for crew and cargo services including to the International Space Station, to the extent possible."

Little or no debate accompanied this adoption process.[12] Griffin discussed COTS in congressional hearings and no one objected. OMB had long advocated commercializing space transportation to save government money. The White House Office of Science and Technology Policy (OSTP) wanted to push technology-based economic development, and Griffin framed COTS as industrial policy. COTS would use Space Act Agreements to level the playing field. These agreements did not require a huge overhead of lawyers and accountants for both government and industry. A Lockheed or Boeing was accustomed to FAR-based contracts, but not the new entrants Griffin wanted to nurture.

The President and Congress focused on Constellation, Bush's high-profile, multi-billion-dollar Moon, Mars, and beyond program. The small COTS program flew under the political radar of top policy-makers, most of whom saw Ares 1/Orion as NASA's shuttle successor. OMB and OSTP staff, however, were both aware of COTS and hopeful the experiment would succeed.

Early Implementation

Lindenmoyer established the Commercial Crew and Cargo Office (C3PO) at JSC, and sent out a request for proposals in early 2006. In line with the Space Act approach, the request did not specify requirements, but asked industry to propose how it would provide certain transport capabilities to LEO. It did not mention ISS. It listed as one capability, "COTS D," that entailed crew rather than cargo transport. NASA was interested in industry ideas, but was not intending to go to crew until companies demonstrated cargo transport. It wanted competition.[13] On August 18, NASA chose Space Exploration Technology Corporation (Space X) and Rocketplane Kistler (RpK), and divided the $500 million roughly equally between them. SpaceX was one of the few companies that had proposed COTS D. From California, it was a new company, having been established in 1992 by a wealthy young Internet entrepreneur, Elon Musk. RpK was based in Oklahoma, nd had longer historical roots, and was led by a former NASA executive.[14]

Both firms were judged on their technical and business plans. Both had to raise a great deal of private money to comply with Griffin's industrial policy goals. They set their own technical and business milestones, and were paid by NASA only when they met them. Most senior NASA officials expected COTS to fail.

Failure looked likely in mid-2007 when RpK ran into financial problems and could not match NASA's contributions, as its agreement required. After several extensions, NASA terminated RpK. Approximately $175 million was unspent. SpaceX said: "Give it to us, and we'll go to COTS D." However, NASA wanted competition—that was a key element of the program.[15] NASA conducted a round two competition and on February 19, 2008 chose Orbital Sciences Corporation, a mid-sized (billion-dollar) aerospace firm well known to NASA.

In 2008 it was SpaceX's turn to have problems—technical challenges with its Falcon 1 rocket, the prototype for its Falcon 9 that was intended for COTS. If SpaceX could not get Falcon 1 to work, it probably could not succeed with Falcon 9. Musk had put $100 million of his own fortune getting to this point. There had been two launch failures in previous years, but in 2008 SpaceX felt the problems had been solved. However, on August 2, 2008 Falcon 1 failed again. Musk expressed confidence in public, but was truly worried. He was running out of money and another failure would probably be too much for his private-investor backers, not to mention NASA. Nevertheless, on September 28, Falcon 1 succeeded.[16]

NASA was relieved at the Falcon 1 success, but knew that SpaceX was falling behind its proposed schedule. Orbital was just getting started. Equally worrisome was that Constellation was having technical and budget difficulties and the gap between shuttle retirement and a possible shuttle successor was widening on that front as well. NASA arranged for Russia to supply cargo through 2011, but what would it do after that? There were budget pressures inside and outside NASA that would normally have led to ending COTS, a small program with limited support. However, that support included Griffin and White House offices, particularly OMB and OSTP.

Within NASA, Gerstenmaier was increasingly worried about ISS supply. As a consequence, he and other NASA leaders reluctantly decided to speed up procurement of services under CRS. Gerstenmaier wanted a seamless transition from development (COTS) to use (CRS).[17] This decision was a major turning point for COTS.

While the CRS competition was open to all companies, SpaceX and Orbital had the inside track. The result was that on December 23, Orbital received $1.9 billion for eight servicing flights. SpaceX got $1.6 billion for twelve flights. This meant that as soon as SpaceX and Orbital finished their COTS demonstrations, they could move on to CRS and the larger funding. This money was a tremendous incentive for the companies to move quickly and successfully through COTS. It facilitated their raising venture capital in the private sector. It sent signals to all observers, Russia included, that NASA and the Bush Administration were serious about the program. It was deemed more critical to NASA's centerpiece, the ISS, in part because Constellation was experiencing delays.

Throughout 2009, COTS implementation moved forward. Meanwhile, controversy erupted over Constellation, particularly the Ares 1 rocket, which critics said was slipping significantly in schedule and costing increasingly more than planned. Griffin defended his rocket and Constellation as a whole. Yet the critics grew in number and strength as the change in presidencies loomed. In November 2009, Barack Obama was elected President.

Evaluation/Reorientation

Soon after the election, an Obama transition team was at work. Leading the space team was Lori Garver, who had been chief policy advisor to NASA Administrator Dan Golden in the 1990s. She worked closely with Jim Kohlenberger, formerly Vice President Al Gore's assistant, who dealt with science and technology policy issues in general.

Everyone knew shuttle succession was a problem that Obama would inherit, but what to do about it? As Garver later stated, she "looked under the hood" of Constellation and saw a program with major issues. Kohlenberger joined her in this concern. Given budgetary expectations, there was simply not enough money for Constellation as it was structured, they believed, and the element most associated with shuttle succession, Ares 1/Orion, was especially troubled. On the other hand, COTS looked like the kind of program the new Administration should back. Moreover, if cargo worked, then commercial crew might also make sense as a shuttle substitute. COTS D seemed a logical segue from cargo to crew.[18]

Griffin strongly disagreed that commercial crew could be substituted for Ares 1/Orion. He was particularly defensive about Ares 1, a rocket he believed was technically sound. By chance, Garver and Griffin met at a book signing at NASA headquarters in December 2008 and reportedly engaged in a tense confrontation over Constellation, with Griffin quoted as saying: "If you are looking under the hood, then you are calling me a liar. Because it means you don't trust what I say is under the hood."[19]

Griffin departed NASA shortly before Obama and his team took charge of the White House on January 20, 2009. It was widely known that Obama was going to appoint Garver as Deputy Administrator of NASA. Kohlenberger soon became Deputy to White House OSTP Director John Holdren. George Whitesides, on the transition team with Garver and a commercial space advocate, quickly joined NASA as Chief of Staff to the NASA Administrator. Who that would be took a while to determine. Obama came to office anxious to work with Congress. He tried out a particular candidate with Senator Bill Nelson (D-FL), who headed the committee that would confirm his choice. Nelson opposed this candidate and urged instead Charles Bolden, a former Marine general and astronaut who happened also to be an African American. Obama did not know Bolden, but went along with Nelson's candidate, announcing the appointment in May.

In the period from January to May, Garver had worked informally with Kohlenberger and NASA's principal budget examiner, Paul Shawcross, on initiatives in space policy that could be begun under the huge American Recovery and Investment Act known as the "Stimulus," which was passed on February 17 to deal with the economic crisis Obama faced as he came into office. Their strategy was to use part of NASA's portion ($150 million out of $1 billion) to accelerate commercial crew via COTS D. They knew there would have to be a new competition rather than simply letting SpaceX, eager to go to COTS D and already aboard COTS, win by default. NASA, however, opposed this acceleration of commercial crew.[20]

So did Senator Richard Shelby of Alabama, ranking Republican on the appropriations committee responsible for NASA's budget. NASA's Marshall Spaceflight Center in his state was responsible for Ares 1 and Ares 5. He threatened to hold up the appointments of Bolden and also Garver, who was nominated when Bolden was announced, unless the money went to Constellation—which already got most of NASA's Stimulus funding. The White House and he compromised on $50 million.[21] Bolden, 62, and Garver, 48, testified together, were confirmed together, and took office together. Bolden had no deep experience or great knowledge about commercial space. He did know that the Ares 1 rocket had problems, however.[22]

When Bolden and Garver took office on July 17, the evaluation of Constellation had expanded. Holdren had appointed Norman Augustine, retired aerospace industrialist, to head a special panel to assess the existing human spaceflight program. The panel was constrained by OMB's budget projections, which called for holding NASA spending in check in the years following 2009. The Augustine Panel was truly independent, but Garver and Kohlenberger expected it to find what they had found—that Constellation was falling behind in schedule and growing significantly in cost. The Augustine panel would thus provide political cover for policy changes they believed essential.

In early September, the Augustine Panel issued a preliminary report whose first sentence declared: "The U.S. human spaceflight program appears to be on an unsustainable trajectory. It is perpetuating the perilous practice of pursuing goals that do not match allocated resources." Calling for an extra $3 billion for NASA, the panel listed five options for human spaceflight, four of which called for replacing Ares 1 with a commercial crew alternative. It felt commercial crew's time had come and NASA should focus on deep space exploration, ultimately Mars. In October, the panel issued its final report, repeating views in the earlier document. While the Moon route to Mars was viable, it said, a "flexible path" that could involve various destinations but not landing was equally possible—and one the panel clearly preferred. The emphasis on commercial crew was repeated, along with a recommendation to increase the budget of COTS, to help ensure cargo success.[23]

Formulating Policy for Crew

The Augustine report shifted the direction of space transportation policy from an emphasis on cargo to crew. Fully accepted by the Obama White House, COTS moved into the later implementation stage of development. The CCDev program, which had been held in check under Griffin, was now a policy proposed for a major push, one much bigger than a $50 million increment under the Stimulus money.

The White House took the lead in determining space policy, based on the Augustine Panel. Garver, Kohlenberger, and Shawcross did the spade work, but many others in the White House were involved, including economic advisors. The decision was made to incorporate a policy initiative on crew in the FY 2011 budget, to be announced in February, 2010. Bolden and Obama met on December 16 and discussed options. A leak from the meeting indicated NASA would get an extra billion dollars to develop a heavy lift rocket akin to, but less expensive than, Ares 5, but Ares 1 would have to go.[24]

The White House and NASA both denied the leak. As the budget process worked to its finality, OMB, headed by Peter Orszag, was powerful. Holdren was also prominently involved. Obama himself was engaged, even though preoccupied with higher priorities of health policy, unemployment, and wars. Bolden was on the periphery of decision-making, not influential. There was little or no information coming from the White House.[25] The widespread expectation was that Ares 1 would end and there would be a boost instead for commercial crew. Under intense time pressure, the White House sought to forge a policy change that would be sustained and affordable given overall financial exigencies. Presented with the options, Obama decided on a dramatically new course.

Adopting Commercial Crew

On February 1, 2010, the roll-out of the Obama budget came. Constellation was terminated. All components—Ares 1, Ares 5, Orion, and Altair—went. The President's Moon program was dead and no destination put in its place. Instead, Obama's budget called for $6 billion to jumpstart a commercial crew industry along with substantial new money for "game-changing" technology. NASA's $18.7 billion budget would go up modestly to $19 billion for FY 2011. Instead of cuts in succeeding years, NASA would get raises—but not amounts the Augustine Panel said were needed. Garver and Kohlenberger answered questions from the media at the roll-out. Bolden read a scripted statement and departed.

The political reaction in Congress was one of shock. Comments were almost all negative, especially from lawmakers representing states most affected by the cancelation (Florida, Texas, and Alabama). NASA as an institution resisted, as did Constellation contractors and their lobbyists. The media found it difficult to get information. Having been largely excluded from decision-making, agency managers had little to say. Many were in denial, as the decision went way beyond the Augustine report.[26]

New entrants—what the media called "New Space"—argued for the policy, as did Garver and Kohlenberger. Bolden spoke up also, but his credibility was weakened by his minimal role at the roll-out. The opposition won the public relations battle. Moreover, thanks to Senator Shelby, NASA's latest appropriations bill, now law, had language requiring Congressional consent to any major change in Constellation. Griffin, in a role unusual for ex-Administrators, spoke out against the Obama policy. Many astronauts, including Neil Armstrong, the first human on the Moon, joined the chorus of negative statements.[27]

With criticism of the President's decision resounding, NASA nevertheless sought to start implementing CCDev. There had been a request for proposals for the $50 million Stimulus. Lindenmoyer was in charge, but the presidential decision, visibility, and prospective amount of commercial crew funding meant that CCDev would be a separate program from cargo, to be legislated by Congress rather than an administrative transition through COTS D. What was now begun under stimulus money was called CCDev1, with succeeding rounds of CCDev to follow. The Space Act mechanism still applied, however.

Proposals were submitted to NASA by 36 companies of all sizes. On February 25, 2010, the day after the controversial budget roll-out, Bolden introduced the winners at Washington's National Press Club. They were Sierra Nevada ($20 million); Boeing in collaboration with Bigelow Aerospace ($18 million); Blue Origin ($3.9 million); Paragon ($1.4 million); and United Launch Alliance ($6.7 million). SpaceX and Orbital had submitted proposals but had not won. NASA was anxious to test different technical approaches. Bolden said each company that won was making substantial investments itself.

Although Bolden had made this announcement, it was Garver who was out in front selling CCDev. She announced that SpaceX and Orbital would be getting $300 million more for COTS, to help them move cargo transport forward more quickly. The opposition to CCDev pointed out that cargo had yet to succeed.[28]

Obama, meanwhile, got the message from Senator Nelson and others with influence that his February 1 roll-out had backfired. He agreed to go to Kennedy Space Center (KSC) in Florida and mend political fences. Florida was a critical state for Obama, and Nelson was running in the upcoming election. The White House consulted NASA on the speech, but largely controlled what was said. Bolden, among others, pressed indirectly to include a destination in his speech, Mars, and bring back some elements of Constellation.

On April 15, 2010, Obama spoke at KSC. He declared that the USA would go to Mars by the mid-2030s, and to an asteroid in 2025. He promised a retraining program for KSC employees laid off after the shuttle retired. He brought Orion back as a crew rescue vehicle, and said he would make a decision at the end of his term on the heavy lift rocket. He held to his decision to terminate Ares 1 and put the funds into commercial crew. He disparaged Bush's Moon goal.[29]

The President's attempt to turn the tide of resistance with Congress failed, and controversy continued. Even the new entrepreneurial firms found fault with the crew rescue vehicle—termed "Orion-lite"—as possible competition for them. The President assigned a top legislative liaison assistant, Rob Nabors, to work with Senator Nelson on a compromise acceptable to legislators. Nelson operated on behalf of a number of key lawmakers in the Senate and House, particularly Senator Barbara Mikulski, responsible for NASA appropriations.

In late September, Congress and the White House came together on compromise legislation Nelson and Nabors had worked out, and on October 11, Obama signed the bill into law. The law softened the controversy, but did not fully end it, and an appropriation still had to be provided in the months ahead. Bolden was caught in the middle of contending forces. He replaced or moved individuals in NASA who were particularly recalcitrant, and pressured senior managers to bring them aboard the compromise. He took this October legislation as the policy he was to implement.[30]

What that policy said was as follows: Constellation as a program was gone, specifically Ares 1. Orion was back with a new name, Orion Multipurpose Crew Vehicle—a larger crew vehicle for exploration than the rescue vehicle Obama had mentioned on April 15. Ares 5, or at least heavy lift, was back with the name Space Launch System, or SLS. Commercial crew was given an official go-ahead. The money authorized for commercial crew, however, was cut back from what Obama had originally requested.

Implementing CCDev2

NASA realized that with the shuttle going (in 2011 rather than 2010 under the compromise legislation) and Ares 1 dead, the choice was commercial crew or the Russians. Hence, the agency gradually acquiesced to the new state of affairs. Conflict was not over, but a different political equilibrium was being established within which the various players would work.

On October 25, NASA solicited proposals for the next round of CCDev from industry. NASA did not have the money to fund any proposals, but hoped it would have the money by March 2011, when the continuing resolution under which it was operating would presumably be replaced with an actual appropriation. NASA would finance research and development on astronaut-relevant subjects such as life-support systems, launch-abort systems, and emergency-detection systems. Garver said NASA wanted to fund four proposals, as it wanted competition.[31]

Phil McAlister served as Director of the CCDev program in Headquarters, with Lindenmoyer continuing with his role as technical manager. On December 8, SpaceX scored a success when it launched its Dragon capsule. This was a long way from a demonstration of an actual cargo delivery to ISS, the goal of COTS, but it was progress and CCDev needed progress in cargo for crew to be acceptable. Bolden was delighted and extolled the “partnership” between NASA and industry.

NASA moved forward as well as it could, given the budget uncertainty. In early February, Obama issued his budget request for federal agencies, and he asked for less in the next fiscal year than he had in the still-not-funded current year, $18.7 billion.

On February 14, NASA contacted eight companies and asked them to come to JSC in Texas to discuss their proposals for CCDev2. The companies were Alliant Techsystems (ATK), Blue Origin, Boeing, Excalibur Almaz, Orbital, Sierra Nevada, SpaceX, and United Space Alliance (USA).

At the beginning of March, Bolden decided on an organization to implement CCDev. The director of Exploration Systems was retiring and Bolden merged Exploration Systems with Space Operations under Gerstenmaier. McAlister remained in charge of commercial crew, under Gerstenmaier but informally also working with Garver. Bolden shifted technical management from JSC to KSC, with JSC as back-up. Ed Mango of KSC would take on the role for crew that Lindenmoyer performed for cargo. Kathy Leuters of JSC would be his deputy. Leuters had been space station liaison with COTS. JSC had Orion; Marshall, SLS. Kennedy now had commercial crew—a major program it needed with shuttle phasing out.

NASA was poised to implement CCDev2 if it could get the money. Finally, on April 14, 2011, Congress agreed on an omnibus appropriation bill that kept the government running for the current fiscal year. NASA received $18.45 billion. The appropriation language followed the NASA Authorization Act of 2010. It ended Constellation officially, amply funded Orion and SLS, and provided $289 million for CCDev. It also augmented COTS by $300 million.

Soon after the appropriation passed, NASA announced four awards: Blue Origin, $22 million; Sierra Nevada, $80 million; SpaceX, $75 million; and Boeing, $92.3 million. McAlister said the goal of CCDev was to nurture a commercial industry that could fly crew to ISS by "approximately the midpoint of the decade." The goal of the second round of CCDev would be to mature technologies that could evolve into a full-scale system. Creating a full-scale system would be the goal of CCDev3. That would be enabled by the $850 million appropriation being requested for FY 2012. McAlister expected the partners to put in 10–20% of overall CCDev costs (Fig. 13.2).[32]

Meanwhile, the last shuttle flight launched on July 8, 2011, a fact that filled NASA and many others with sadness—but which also spurred the agency to push Congress to appropriate the money for CCDev for which the President had asked. The Congressional space committees, however, favored Orion/SLS for funding.

Fig. 13.2 An illustration of Blue Origin's Orbital Crew Spacecraft. With an objective to be compatible with several different rockets, it was announced in 2010 that Blue Origin intended to launch this spacecraft atop the Atlas V rocket. (Blue Origin, NASA image number KSC-2011–8115, public domain.) (Available at https://images.nasa.gov/#/details-KSC-2011-8115.html)

CCDev2 was under the Space Act Agreement, but NASA debated when to switch to Federal Acquisition Regulation procedures. Senior managers argued for doing so when NASA moved to CCDev3. That was when firms would shift from components to an integrated system. Mango in July discussed that prospect with industry and received strong push-back from "new space" firms. They knew they would have to hire additional lawyers and accountants and the traditional firms would be advantaged in any competition. Mango emphasized that NASA had to certify the spacecraft as safe for astronauts and it could not do that unless FAR applied and NASA set the specifications.

In another NASA meeting with industry, Garver spoke and said the agency was evolving, but its culture was slow to change. Garver pointed out that she favored the COTS approach for CCDev, but industry had to understand the dominant NASA view. Astronaut safety was a very emotional issue at NASA. It was the "heart and soul of NASA." That made it hard for NASA to turn over to industry the job of building commercial crew vehicles without maintaining the traditional managerial oversight that FAR provided.[33]

Complicating commercial crew was the continuing debate over priorities. The White House favored commercial crew over SLS/Orion, and Congress the reverse. To be sure, SLS/Orion got more money by far. However, for Congress, the President's figure for SLS/Orion was inadequate, and it pushed for more—taking it from commercial crew if necessary. The most contentious dispute was over SLS.

Bolden in June chose the SLS design and sent it to OMB for approval before public announcement. There it sat. OMB wanted to know long-term costs and apparently was skeptical of NASA's numbers, and wanted independent estimates. As the summer continued, Congress—particularly SLS advocates such as Senators Nelson and Kay Bailey Hutchison (R-TX)—fumed. Exasperated, they threatened to subpoena Bolden to get information on the design.

On September 7, a *Wall Street Journal* article claimed SLS would cost \$62.5 billion for development. Congress had estimated it at \$18 billion. Nelson and Hutchison exploded and blamed the White House for the leak and a blatant attempt to undermine the October 2010 compromise. Hutchison was the senior Republican on NASA's authorizing committee and also on NASA's appropriations committee. They got Obama's attention.[34]

The next day, OMB director Jacob Lew met with Holdren and Bolden. Although the SLS matter triggered the meeting, there was the larger and worsening Congress–White House debate over the budget generally. In an environment in which an across-the-board "sequester" of federal funds hovered over discussions, where would the line be drawn for NASA on top priorities? Lew said he could speak for the President. The men decided that Obama wanted the ISS continued and funded; Congress (Nelson, Hutchison and others) wanted SLS/Orion; and Congress (Senator Barbara Mikulski) insisted on the James Webb Space Telescope. These were the "big three" priorities. However, ISS required commercial space and all priorities needed investments in advanced technology, so these two were enabling priorities for the White House. All these components were in the original October 2010 authorizing act, but there seemed to be a need to restate them, if only to send a strong signal to all interested parties, including Lew's own organization, OMB. Lew volunteered to go with Bolden to see Nelson and Hutchison so they understood Obama was serious about reaching agreement, and he did so.[35]

It was the SLS matter that had been the focus of the current controversy, and on September 14 the two senators, Bolden, and others (not Lew) announced that NASA was going ahead with SLS. The Bolden design was approved and the costs were what Congress (and NASA) said they were: $18 billion for development. This rocket in question, however, would be evolvable, and ultimately be capable of taking astronauts to Mars.

This September decision helped greatly, but did not completely end the debate over priorities, and commercial crew's place among them. On November 21, 2011, Congress passed the government's and NASA's appropriation. Down from the previous year, NASA got $17.8 billion. Congress provided less than half the requested $850 million for commercial crew: $406 million. Showing distrust of the White House, Congress ordered that $100 million of the sum be withheld until Bolden gave House and Senate appropriations committees a written notice that NASA was actually proceeding with SLS acquisition. Obama signed the legislation on November 18.

With less money, Bolden had to push the start of commercial crew operations back, from 2016 to 2017, and that meant relying on Russia that much longer. In late December, NASA announced it would stay with Space Act in CCDev3. That meant the money NASA had for commercial crew would go further, and NASA could stick with its intent to fund two or more partners. This was Bolden's decision, opposed by virtually all his senior managers and advisors—except for Garver, who strongly espoused the Space Act approach.[36]

The House had gone into Republican hands in 2011 and Ralph Hall (R-TX) chaired the House Space Committee. He pressed NASA to go down to one company, and to use FAR to assure safety. It was no secret he wanted NASA to go with an established company, presumably Boeing, and not SpaceX. NASA resisted, wanting to keep its options open, granting SpaceX's wish to combine its last two demonstration flights under COTS, and desiring to get to the operational stage of cargo as soon as possible.

Later Implementation: CCDev3

On February 7, 2012, NASA announced a competition for its third round, formally called Commercial Crew Integrated Capability (CCiCap). Given limited resources, NASA said it had $300–500 million for proposals for an integrated system. The fourth and final round would entail demonstration of crew delivery and certification by NASA. It would be under FAR.

A few days later, Obama released his budget proposal. Under great pressure to hold federal spending down, he set $17.7 billion for NASA, another cut below the current year. He requested $830 million for commercial crew. Hutchison and Shelby complained that Obama took money from SLS/Orion to give to "speculative 'commercial' providers" who would "overpromise and under deliver." They made it clear that Congress would impose its will. Nelson offered little defense from the Democratic Party side. Space policy was typically not partisan; it was regional. McAlister complained that if Congress gave NASA only half its request, the program would not get to where it needed to go.[37]

Congressional hearings on commercial crew did not go well. The opponents seemed to have the momentum. The Senate cut the crew budget by $300 million. The House appropriations committee not only cut commercial crew, but adopted language directing the agency to go down to one or two companies. It preferred only one, and threatened more cuts to force the issue. NASA, and commercial space, desperately needed something to turn the political tide.

SpaceX Comes Through

On May 22, 2012, at 3:44 a.m., SpaceX's Falcon 9 rose from Cape Canaveral carrying an unmanned version of Dragon aimed for ISS. There had been one postponement after another, and the flight was well behind the original schedule. But all went extremely well. SpaceX leader Musk was elated. So was NASA Administrator Charles Bolden, as their words at the beginning of this chapter reveal.

Once again, "It's a great day for America. It's a great day for the world," Bolden told reporters afterward. "There were people who thought that [NASA] had gone away [with the 2011 retirement of the space shuttle]. But today says, no we've not gone away at all. We've got the SpaceX–NASA team, and they came through this morning with flying colors."

Griffin, who had initiated COTS, had to feel vindicated, although he had strongly opposed Obama's commercial crew policy. [38]

A few days later, SpaceX delivered cargo safely, and subsequently splashed down in the Pacific. NASA had allowed SpaceX to conflate its final two demonstration flights into this one. It was a risk, but the agency and firm felt they were ready, and they were right. The critics in Congress had to take note, and did so, giving grudging praise. SpaceX thus ended its COTS participation, moving ahead to CRS (commercial resupply) and the huge financial incentive it promised.

What the flight meant for commercial space was desperately needed credibility. It meant that COTS as a program was working. Orbital was scheduled for its final demonstration flight in 2013. The trade publication, *Space News*, commented that the SpaceX flight had changed the political dynamics, improving the prospects of greater funding for the commercial crew program.[39]

On May 31, the same day SpaceX completed its demonstration, Bolden and Congressman Frank Wolf, chair of the House subcommittee responsible for NASA appropriations, reached agreement on moving forward on commercial crew policy. Wolf had wanted to cut NASA's budget to force the agency to go to one contractor, most likely Boeing. However, SpaceX had proved its case and gained widespread favorable publicity. He was now willing to compromise.

On June 4, Bolden wrote Wolf confirming the understanding they had reached. The next day, Wolf publicly announced the deal. He agreed to a funding level for CCiCap at or near the Senate appropriations committee approved amount, $525 million. This would allow NASA to proceed with 2.5 partners under the Space Act—that is, two full awards and one partial award. Bolden agreed to say that the "primary" purpose of the commercial crew program was to serve ISS and "not the creation of a commercial crew industry."[40]

CCiCap now advanced with more certainty. Boeing, SpaceX, Sierra Nevada, ATK Aerospace, Spacedesigns, Space Operations, and American Aerospace were in the running. On August 6, NASA announced the winners: Boeing would receive $406 million over the 21–month project duration, SpaceX would receive $440 million, and Sierra Nevada would be granted $212.5 million. A few days later, NASA stated it would provide relatively small ($10 million) contracts under FAR to the winners so NASA could direct them more explicitly on safety certification design standards.[41]

On October 7, SpaceX launched Dragon to ISS on the first of 12 operational flights to ISS. This enabled SpaceX to receive the $1.6 billion CRS money. There was a palpable sense that with the SpaceX achievement and Bolden–Wolf agreement, commercial space had reached a turning point in both technical and political momentum.[42]

As 2013 began, the issue was not whether commercial crew was coming, but how fast. With the larger White House–Congressional debate over budgets continuing, the question for NASA was how to divide a smaller appropriation. It was not until March 21 that Congress passed legislation funding government for the remainder of the fiscal year, only six months of which remained. NASA received $16.6 billion, commercial crew $489 million. While less than the $830 million Obama had requested, it was better than the $406 million the previous year.

On April 5, Obama proposed his next year's budget, $17.7 billion for NASA, with $821 million for commercial crew. While the focus of policy discussion was on money, the various companies involved in cargo and crew made technical progress. For example, on April 21 Orbital launched its Antares rocket on the next-to-last test in its COTS program.

CCDev4 Begins and COTS Ends

In July 2013, NASA announced that the final round of CCDev would begin in summer 2014. This would be called Commercial Crew Transportation Capability (CCtCap). It could be the certification phase of implementation. This was when NASA's evaluation, based on demonstrated performance serving ISS, would take place. A test flight would be required. FAR would apply.

At the end of July and beginning of August, congressional committees approved NASA appropriations for the upcoming year. The House appropriations committee allowed $500 million for commercial crew, while the Senate approved $775 million. Although below Obama's requested $821 million, the resulting compromise was expected to be the largest funding yet.

On September 6, Garver departed NASA to manage the Airline Pilots Association. A "lightning rod" for criticism from opponents because of her strong advocacy of commercial crew, she was one of the most outspoken and influential deputy administrators in history. She declared: "I actually do feel that so much of what I set out to do is being accomplished."[43] As if to prove her point, on September 18

Orbital launched its final cargo demonstration to ISS. It was a success. Orbital thus "graduated" from COTS to CRS. COTS ended as a budgetary line item, and cargo flights were institutionalized under the ISS budget. Virtually everyone who commented called COTS a success. Commercial crew had a long way to go, but it was deep into its implementation stage.

On November 25, NASA issued an RFP for the final round of CCDev. While any company could make a proposal, the three firms working in round three clearly were advantaged. In early 2014, Congress appropriated $17.6 billion for NASA, a $700 million raise over the previous year. It included $696 million for CCDev, less than Obama had requested, but the most so far. The technical and political trends were favorable. On September 16, NASA announced that Boeing and SpaceX were the winners. Boeing received $4.2 billion and SpaceX, $2.6 billion. Each company got what it proposed. Bolden made the announcement. Kathy Lueders had replaced Mango, who had to leave his management post to deal with legal matters unrelated to CCDev. Lueders had been deputy, and before that JSC liaison on COTS for ISS. She would move to Kennedy to run the final round. Bolden stated: "Today, we are one step closer to launching our astronauts from U.S. soil on American spacecraft and ending the nation's sole reliance on Russia."[44]

Toward Cargo Institutionalization

There was more to do before commercial crew reached operations, and there would be setbacks. Orbital suffered a cargo launch failure in 2014; SpaceX endured another in 2015, but it returned to flight the same year. It was problematic whether Boeing and SpaceX could meet NASA's 2017 deadline for demonstrating their ability to transport astronauts to the International Space Station. However, in late 2015, Congress provided for the first time all the money NASA had requested for commercial crew: over $1.2 billion. The question about commercial crew was when, not whether. A major policy change was coming to be widely accepted.

Conclusion

The commercial cargo and crew program has come a long way toward achieving its goals. Cargo transport is a success. Moreover, NASA will likely succeed in crew, as CCDev is deep into its implementation stage.

Commercial cargo has transitioned from development under COTS to operations under the CRS activity. The goals originally set for it were to nurture a new industry and service ISS. The COTS program helped to do both. It gained for NASA two new rockets and spacecraft at costs lower than would have been the case with government money alone. And it helped greatly to bring SpaceX into aerospace, a firm that has been a disruptive and energizing force ever since, going from 100 employees to 3000 during its time under COTS, adding additional talent under commercial crew. While COTS (and crew) cannot be said to have created a new industry, they have surely brought major change to the aerospace industry. This change has added to competition and lowered prices to government.

Commercial crew has yet to succeed fully, but is likely to reach institutionalized operations. NASA cannot let it fail, lest it continue to depend on Russia to transport astronauts to ISS—a fate for which few outside Russia wish. However, commercial crew is much more a misnomer than COTS. NASA invested $800 million in COTS; industry spent approximately $1 billion. In the case of CCDev development, the ratio is much more skewed—the government's share sits between 80 and 90 percent. That is still better than traditional contracts where government pays all plus a fee. As for industrial policy, that goal has diminished as an overt objective, due to the ideology of Republican lawmakers in Congress and the realities of ISS needs.

NASA's requirements for both cargo and crew have grown substantially over time. The Obama decision to kill Ares 1 took commercial crew from a back-up to Ares 1/Orion to an imperative. That imperative enlarged when US–Russia relations deteriorated over Russia's invasion of Crimea.

COTS is a success. CCDev represents "success so far." The political winds were behind COTS, which escaped political controversy. CCDev ran into a storm of political conflict. Its movement from agenda-setting to implementation revealed struggles and delays, with many in Congress slow to be persuaded of its merits. Many NASA managers were also skeptical of commercial crew. They demanded safety measures and FAR contracts to rebalance power in government's favor. Only in the FY 2016 omnibus appropriation bill did Congress grant NASA the full amount of money it requested for commercial crew.

Nevertheless, both programs show that government can innovate in public/private relations. Government has provided push via development money and pull through its user role. The private sector has taken risks and put "skin in the game." The Space Act approach has worked, and the hybrid model of contracting employed in the later rounds of CCDev has arguably also been efficacious, at least in winning support within NASA and on Capitol Hill. That approach entails the Space Act for early development, FAR for later development and operations. There has been compromise on some of the most cutting-edge concepts in both COTS and CCDev, but there has also been real change. A key factor that has been critical in this innovative program is that SpaceX came along when it did. It has been the constant force across the cargo and crew programs. If government was to innovate in a public/private partnership, it had to have an innovative partner. It had one in SpaceX, which became the public face for commercial cargo and crew and has helped the USA compete in the global launch market. Finally, there was a political split between new space and old space, and their supporters, as COTS and CCDev advanced. By choosing SpaceX and Boeing for round 4 of CCDev, NASA has gone some distance in meliorating the schism.

COTS and CCDev represent more a case of policy and institutional innovation than technological innovation. For a time, the words "space taxis" were applied to commercial spacecraft as if to emphasize their simplicity. They are far more complicated than that, as indicated by the multi-billion-dollar cost of commercial crew. However, technological innovation was not the direct goal of the architects of COTS and CCDev. What these programs emphasized were values of reliability and especially safety for CCDev. They also emphasized values of cost-saving. These were the prime drivers in the political construction of the technologies at issue.

Still, there was the hope—especially by Griffin and in the White House—that NASA could catalyze change in the staid aerospace industry through encouraging nimbler, smaller, and newer companies to enter the field. Technological innovation might therefore emerge as a byproduct of commercial cargo and crew. And SpaceX in particular has been highly vocal about its desire to push the technological frontier. It has worked to develop a new rocket that would be more fully and rapidly reusable than is presently possible. On December 21, 2015, SpaceX not only returned to flight, but was able to land the first stage of its Falcon 9 rocket. It was not the first organization to accomplish such a rocket landing, but it was "the first private company to conduct a vertical take-off and landing (VTOL) of a rocket on an orbital (rather than suborbital) trajectory successfully."[45] If it can build on this technical success and show the commercial viability of reusability, that would be an innovation that would be potentially revolutionary in its impact in driving down costs of launching. Other companies are seeking to develop reusable rockets in order to compete with SpaceX, and one, Blue Origin, landed a suborbital rocket prior to SpaceX's feat.[46] Thus, the commercial cargo and crew program could indirectly lead to quite significant technological innovation. Time will tell.

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CHAPTER 14

Conclusion: What Matters?

Roger D. Launius and Howard E. McCurdy

Innovation is a term not commonly associated with government. When asked to identify the characteristics that distinguished their sector, a panel of business managers ranked innovativeness as one of their top attributes. (They also emphasized profitability and honesty.) Innovation was not cited as typical of government operations by a corresponding panel of public executives.[1]

In a seeming contradiction of this finding, officials at NASA list innovation as one of their principal concerns. NASA's mission statement directs its participants to "reach for new heights and reveal the unknown" and "make life better … on Earth." An explanatory statement is sprinkled with words like "Giant Leap," explore, knowledge, technology, and innovate.[2]

Yet the statement offers no guarantee of success. When charged with the development of a new Space Launch System (SLS), NASA officials boasted that the giant rocket required few new technologies. SLS

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is the rocket being developed to transport astronauts to the Moon and beyond. The rocket uses RS-25 main engines left over from the space shuttle program—the actual engines employed on the shuttle orbiters, fifteen in all. The rocket's first or core stage consists of an elongated version of the space shuttle's external fuel tank. Added thrust is provided by two solid rocket boosters (SRB) that employ a shuttle SRB design with one added segment. "Rather than reach for advances in rocketry," wrote one observer, "engineers are to use proven technology." By the time the rocket flies in the 2020s, said another, it will be using fifty-year-old technologies designed for a launch system approved by President Richard Nixon in 1972.[3]

A product need not utilize a new technology in order to be innovative. As Chap. 8 on repurposing NASA spacecraft shows, old technologies may be recombined or used in ways that make them innovative. By definition, an innovation is a new idea or a more effective device or process. If the product is more effective (cheaper, faster, smaller, or more accessible), it is by definition innovative.

SLS managers insist that they have neither sufficient time nor enough money to develop new technologies.[4] The managers plan to reduce the number of people needed to build the rocket and use some technology advances such as stir-friction welding, but the basic program is designed to avoid new technologies for lack of time and money. This would prove innovative if it increased capacity, cut time, or reduced cost. Yet preliminary analysis suggests that the SLS rocket will cost more and take more time to produce than an equivalent Saturn V. According to a study prepared by the Government Accountability Office (GAO), the engineers have seven years to prepare for the first flight (scheduled for late 2017) and will consume $8 billion by 2018. This is not an appreciable advance over previous launch systems.[5]

More than a half-century earlier, as President John F. Kennedy considered whether to commit the USA to land Americans on the Moon, a high-ranking NASA official assured the study team that the venture would require "no invention or breakthrough" to complete the task. As John M. Logsdon commented, the lunar landing was unique in that it required no new discoveries, "just mastery over nature using the scientific and technological knowledge available in 1961." Project Apollo required advances in computer miniaturization, engine development, orbital rendezvous, and a host of technologies designed to preserve the lives of the astronauts, including spacesuits. Still, the observation revealed an important truth that largely proved true: civil servants successfully reassured skeptical officials whose consent they needed by observing that the initiative would not require them to invent something new. "Innovations, yes," Logsdon later noted. "Inventions, not needed."[6]

In stark contrast to this experience, officials at NASA's Jet Propulsion Laboratory developed a series of Mars rovers exhibiting low cost and high technology. NASA's experience with landings on Mars began with the 1976 Viking mission. The whole Viking mission (two orbiting spacecraft, two landers) cost $1.1 billion—the equivalent of $3.9 billion in the purchasing power of the aerospace dollar during the development of the first rover mission twenty years later. Once they reached Mars, the 1976 landers did not move. They did their work in place. The rovers traversed—the first one (Sojourner) a few meters, the next two (Spirit and Opportunity) combined more than 35 miles. Though it lacked the capability of the Viking landers, the inaugural rover mission was highly innovative, both from the cost and technology perspective. The mission (one lander, one robotic rover, landing in 1997) cost $265 million. It employed a never-before-tried airbag landing system. Reversing the commonly cited observation that lack of time drives up cost, the Pathfinder team kept costs low by designing, fabricating, and launching the lander/rover spacecraft in just three years. Amplified by a similar history established by the Near Earth Asteroid Rendezvous team at the Applied Physics Laboratory (a NASA-financed project), the two undertakings formed the basis for a broader number of low-cost, highly automated Discovery-class missions.[7]

NASA is a government organization. As this volume suggests, it is capable of managing complex technologies. Its mission statement embraces discovery and innovation. Yet it is also capable of developing programs that rely on existing technology, require little invention, and cost billions of dollars. Summarizing the work that precedes it, this chapter seeks to explain why. Under what conditions does innovation appear in this government-run operation?

Some Hypotheses

The twelve case studies contained in this volume help to illuminate many of the issues that affect innovation in government. The literature on public innovation is rich with propositions. Some commentators express skepticism about the capacity of public institutions to spur innovation. Others acknowledge the reality that modern governments are inexorably drawn to attempt it in areas such as national defense, space exploration, and health care. Many characterize the innovation process. A summary of important points from that literature follows:

1. Innovation is good. Economists and public officials generally agree that technological innovation improves human welfare. It is associated with economic growth, higher standards of living, political stability, intellectual enlightenment, and the ability to overcome the limitations imposed by resource consumption and population growth on a planet with a fixed land mass.
2. Innovation is evolutionary, complex, and nonlinear. Most observers agree that innovation is an evolutionary, spontaneous process. It does not lend itself to simple cause-and-effect representation. It is hard to create. As such, it is not something that can easily be purchased with a government contract, as one might write an order for a conventional product.
3. Innovation is public, although observers disagree as to whether this is good. Since the mid-twentieth century, governments in countries with advanced economies have used tax revenues to supplement private-sector spending on research and development (R&D). Progressives believe that this is necessary to account for shortcomings in the private sector. According to this point of view, industrialists under-invest in innovation—the sort of research that takes place in industrial laboratories. Conservatives and libertarians remain skeptical. They suspect that much R&D government spending displaces private contributions and does so with less effectiveness than private-sector spending.
4. Innovation is risky. The evolutionary nature of innovation makes success uncertain. At the same time, economically advanced countries maintain a large government presence in discovery. People from across the political spectrum worry about the capacity of governmental bodies to make innovation work. Governmental bodies, they observe, tend to be too conservative or too susceptible to the efforts of special interests seeking protections against the forces of disruptive change. The suspicions kindle a substantial debate over the appropriate level of government support for R&D.

5. Partnerships may help to expedite innovation. The observations thus far counter the desire for innovation and the governmental presence in attaining it against the uncertain nature of innovation and the difficulties inherent in using government bodies to achieve it. Increasingly, public officials have turned to public/private partnerships as a means of balancing these forces. Partnerships harness the ingenuity of people in the free enterprise system with the assets of government, and may compensate for the presumed weaknesses of efforts at public-sector innovation.

As the case studies in this volume document, the US space program has more than a half-century of in-depth experience with partnerships of various kinds. In addition to the use of conventional government contracts for the purchase of services, NASA has engaged in partnerships for international cooperation, partnerships for the development of new technologies, partnerships aimed at commercializing orbital services, partnerships that encourage the formation of new space industries, partnerships that allocate research time on government facilities, and partnerships to encourage competition and low-cost innovation. NASA has also innovated on its own.

The cases suggest that the public/private innovation model is more complex than previously imagined. In a sentence, partnerships are no guarantee of innovation. The conventional government procurement model is very strong and efforts at innovation easily slip into the traditional mode. Innovation requires commitment as well as appropriate frameworks. A more detailed description of the aforementioned points follows, followed by a summary of the experience contained in the twelve cases (Fig. 14.1).

Innovation Is Good

Economic data provides the conventional justification for innovation. Economic growth correlates very well with investment in R&D. (Note that we say correlates. A causal relationship is harder to establish.) According to data collected by the World Bank, the richest nations of the world spend upward of 4% of their Gross Domestic Product on R&D. That includes both public and private sources. Between 2011 and 2015, the USA spent 2.8%. Less wealthy countries spend less.[8]

Fig. 14.1 Partnerships such as the one that NASA fashioned with the Orbital Sciences Corporation to deliver cargo to the International Space Station can help foster space flight innovation. Here Orbital's Cygnus spacecraft is readied for its mission on October 23, 2014, at the Horizontal Integration Facility at NASA's Wallops Flight Facility in Virginia. (NASA/Patrick Black, public domain) (Available at https://www.nasa.gov/content/goddard/orb-3-fairing-installed-002.)

The correlation between wealth and investment is famously represented by a chart in Terence Kealey's *Economic Laws of Scientific Research*. Because they are richer, wealthy nations have more disposable income to invest in R&D. Innovation encourages growth; economic growth allows more investment in innovation. Conversely, poor nations find themselves trapped in a cycle of consumption and resource depletion from which they cannot easily escape.[9]

In the mid-twentieth century, a number of commentators warned of the combined effects of resource depletion, environmental degradation, and population growth. The various models suggested catastrophic consequences (particularly a plunge in population) in the mid-twenty-first century. NASA officials even encouraged Princeton physicist Gerard O'Neill to study the feasibility of moving millions of inhabitants off the planet onto space colonies.[10]

The solution to this Malthusian doomsday revelation lay in technological innovation. By inventing more efficient forms of energy production, transportation, manufacturing, and communication, Earthlings could stave off the worst consequences of population growth and resource depletion.[11] Commentators disagreed on other aspects of this scenario, particularly the role of government in exciting invention, but they did not disagree on the value of innovation.

Supporters of technological innovation used twentieth-century history to demonstrate the value of technology. Certainly, the effects were not all positive: Ninety eight million humans died in two world wars made more efficient by advances in weaponry. Yet great advances occurred in life expectancy, material comfort, and reduction of infant mortality. A person born in the USA in 1900 could expect to live 47 years; by 2007, life expectancy had increased to 78. On the whole, twenty-first-century individuals living in nations with advanced technologies were healthier, better fed, and safer than those living in the same places one century earlier.[12]

Innovation Is Evolutionary, Complex, and Nonlinear

If technological innovation is so beneficial, why do people not invest more in it? The answer, in short, is that innovation is not easy. When governments and private firms invest in simpler activities, they often use logic models to predict the consequences of their actions. Logic models are linear. An increase in crime may cause city officials to hire more police to make more arrests, which in turn is designed to reduce crime and result in a public feeling of greater safety. That is a linear logic model.[13]

Innovation is notoriously nonlinear. In his provocative book on *The Evolution of Everything*, Matt Ridley explains "how new ideas emerge." New technologies, he says, arise spontaneously wherever competition exists. Innovations often occur when inventors tinker with existing technologies in an effort to improve them in small ways. Science frequently works backward, he suggests. A technological improvement like the steam engine may prompt scientists to understand the principles governing its operation, such as the second law of thermodynamics. Money invested in basic research does not automatically lead to innovative products at the other end of the fiscal pipeline. It may increase basic understanding, but it may not produce new products that transform the world.[14]

Consider the light bulb as an illustration. As children, we were taught that Thomas Edison invented the light bulb in 1879. The assertion exalts invention as a process of discovery in which a single visionary individual with great technical skill creates a transformative product. In fact, notes Ernest Freeberg, author of *The Age of Edison*, invention is a much more complex process.[15] By the second half of the eighteenth century, a large number of individuals in various countries were racing to prepare a workable incandescent bulb. In the USA, William Sawyer, Albon Man, and Nikola Tesla competed with Edison for patent and manufacturing rights. Edison borrowed shamelessly from them, garnering the lion's share of the credit for electrification.[16]

History suggests that invention is a process that can be nurtured and encouraged, but not centrally controlled. Ripley insists that invention cannot be ordered from above, an approach he characterizes as the creationist approach to innovation. Government executives cannot order their field centers to invent anti-gravity boots or space elevators, technologies whose time has not yet come, but they can create conditions that expedite the course of discovery. The best that social institutions can often do is not get in the way of innovation and support small efforts that lead to big ideas. The case histories in this volume provide interesting insights into the nature of innovation complexity in the realm of space.

Innovation Is Public

During the early stages of the industrial revolution, much R&D took place in industrial laboratories. Among the most famous were the Edison's Menlo Park facility. With the advent of World War I, government R&D spending increased sharply. Such organizations as the National Advisory Committee for Aeronautics, Naval Consulting Board, and the National Research Council joined the National Bureau of Standards as government laboratories. This continued thereafter and, during the World War II and Cold War eras in the USA, Congress created a plethora of agencies devoted to the funding of scientific inquiry. Establishment of the Office of Scientific Research and Development and the National Science Foundation solidified the practice of using public funds for broad-based scientific research.[17]

Governments make significant contributions to overall R&D. In 2011, the latest date for which a full analysis was available, the USA as a whole spent $428 billion on research and development. That included industry, all governments, foundations and philanthropic organizations, and institutions of higher learning. Governments as a whole contributed $129 billion, or 30% of the total sum. Government bodies dominated the provision of basic research (54% of $74 billion spent in 2011), participated significantly in expenditures for applied research (37% of $82 billion spent), and maintained a presence in development (22% of $272 billion spent).[18] Much government spending goes toward research on health ($31 billion in 2011); a substantial portion appears in accounts devoted to the development of new weapons systems ($75 billion in 2011).[19]

NASA's overall budget for fiscal 2011 was $18.4 billion. Of that amount, $6.6 billion appeared in the national R&D accounts. Oddly, much of what NASA does falls outside the classification of R&D. A substantial share of the non-R&D activity at NASA consists of expenditures needed to operate large facilities and provide space transportation.

Advocates of government spending insist that the government presence is necessary to adjust for imperfections in private markets. The imperfections, particularly what is known as the spillover effect, presumably cause industrialists to under-invest in R&D in spite of the innovations such spending produces. The spillover effect is a type of market failure that arises from the free-rider problem. An industrialist who makes a discovery cannot easily prevent a competitor from using the knowledge contained in the discovery. The knowledge spills over to anyone with the capacity to understand it. In theory, this should prompt inventors to wait for someone else to do the research necessary to generate profits.

Political and economic conservatives, especially neoliberals, doubt the logic behind this assertion. Progressives over-estimate the size of this spillover effect, they argue. An industrialist borrowing (some would say stealing) someone else's information needs to spend a great deal of money to master the technology necessary to understand the discovery. In some cases, it is cheaper to replicate the discovery than to appropriate the design.

Conservatives are more concerned with the displacement problem than the spillover effect. In the displacement problem, the government uses its taxing powers to collect funds from corporations and individuals, which the government then returns to the economy with the provision that the money be spent on research and development.

Here is how the displacement effect works in practice. In 2011, the latest year for which complete figures are available, the federal government borrowed and taxed sums amounting to $70 billion that it directed toward basic and applied research. (This does not include an additional $59 billion that the government devoted to development—the creation of new products and services.) The federal government kept $24 billion for itself and sent $5 billion back to industry for use in research. It then transferred the bulk of the remainder—$39 billion—to colleges and universities.

Conservatives worry that much of the money diverted through government is lost to inefficiencies, diversions, and various frictions. They believe that the $70 billion would be better spent if left in the private sector, where it might be spent on basic and applied research. University and college presidents, beneficiaries of the income transfers produced by government spending, naturally object. Public officials worry that money left in the private sector would not be spent on basic and applied research for the reasons noted above.

This raises a central issue in the public/private debate over government support for R&D. How efficient are national governments in their support of R&D?

Innovation Is Risky

Investment in most forms of R&D is notoriously risky. Most inventors can expect to fail. The nonlinear nature of invention and discovery makes success elusive. For every Edison, one can typically find more than a dozen inventors who went broke promoting their ideas.

The essential issue in this observation is not whether innovation involves risk and failure (it does), but the degree to which various institutions possess the capacity to overcome the limitations that make failure more likely. In this regard, government bodies are suspect. Many people (both liberals and conservatives) believe that government bodies possess characteristics that make publicly funded innovation difficult by comparison to the private and nonprofit sectors. In a phrase, government work is driven less by the statement incorrectly ascribed to Apollo 13 flight controller Eugene Kranz that “failure is not an option” than to liberal economist Larry Summers’ observation that government is a “crappy” venture capitalist.[20]

While imperfections in the private market may prompt entrepreneurs to under-invest in basic and applied research, imperfections in the nonmarket (government) can prompt public officials to make dubious investment decisions of questionable worth. The list of complaints is long. Economist Anthony Downs insists that government laboratories have a natural tendency to grow more conservative with time, investing in practices that maintain existing facilities and programs at the expense of the innovation that occurs when the bureau is young. Political scientist Theodore Lowi famously noted the tendency of special interests to use government powers to raise funds for activities that would never survive the rigors of entrepreneurial review in the private market. The practice, Lowi asserts, renders agencies so captivated incapable of change. Economists have a phrase that represents these tendencies, "rent-seeking," a situation that occurs when a group increases its share of existing affluence without creating new wealth.[21]

The matter resolves itself into a Goldilocks problem. Terence Kealey insists that governments over-investing in research degrade their nations' economic growth. He writes:

> Economic, technical and scientific growth are free lunches. Under laissez faire they just emerge, like grass after the rain, through the efforts of individual entrepreneurs and philanthropists. Once the State has initiated the rule of law and sensible commercial legislation, the goodies will flow—and laissez faire is morally superior to dirigism as it maximizes the freedoms and responsibilities of the individual.[22]

Yet we know from experience that activities like space exploration could never command the levels of private investment needed to explore the Moon, planets, and stars. The same can be said for basic research for health and applied research for national defense.

Somewhere between "too much" and "too little" lies a point at which the combination of private shares and public investments maximizes the advantages inherent in discovery. That is what makes the study of partnerships so important. Partnerships provide a mechanism for combining the advantages embedded within each sector. As some of the cases in this volume suggest, partnerships improperly applied also run the risk of capturing the worst tendencies of both.

Partnerships May Help to Expedite Innovation

This volume is concerned with the degree to which partnerships provide a means for promoting discoveries funded by public bodies (in this case NASA) in the presence of the challenges (some would say disadvantages) imposed by innovation through government.

A partnership in its purist form requires the nonpublic entity to risk some of its own capital in exchange for the opportunity to commercialize the resulting discoveries. The nonpublic entity may be an industry, a nonprofit organization, or a university-chartered laboratory. The exact form matters less than the opportunity to profit from the discoveries that government funds help make possible. Partnerships contrast sharply with conventional government contracts in which the government pays an industry or other entity to produce a good or service that the government plans to use. Although they may result in innovation, conventional government contracts are an extension of the government acting alone.

Advocates believe that the partnership form provides added incentives for the nongovernment entity to engage in innovative activities and profit from them. In addition, the partnership provides a source of funds to which the nongovernment partner otherwise might not have access. The twelve case studies presented in this volume reveal NASA's experience with a variety of forms designed to encourage innovation—some pure partnerships, some more or less conventional contracts, and others in between.

Lessons from the Case Studies

The case studies in this volume represent a useful set of examples from which to draw helpful concepts with applicability beyond their individual stories. Moreover, they suggest how broadly contested the concept of innovation actually is, and how it might be rationalized. At sum it is, as Benoît Godin notes, a process for "introducing change into the established order." So, it is also at sum a political transformation.[23]

We may boil down the lessons to be gathered from these case studies into seven basic principles. First, under favorable conditions, government bodies like NASA are capable of innovation. Although public agencies are not noted for their capacity to innovate, they are capable of doing so, occasionally alone or more often through arrangements with other bodies. The transformation of Combat Information Centers into NASA

Mission Control Centers and their ubiquitous reappearance as crisis control centers in existence around the world provides a useful example. While the government contract is not a strong instrument for enticing innovation, as may be seen in the stories of the X-33 development effort and the science conducted on the International Space Station, it is nonetheless possible to write a government contract for a product (such as the Apollo Guidance Computer) that encourages innovation.

Second, while most people view innovation as largely a spectacular and sudden accomplishment, these case studies demonstrate a more evolutionary, nonlinear, and (upon close inspection) extraordinarily complex process. This may be seen in several settings, particularly the Apollo Guidance Computer history. As this case demonstrates, innovation often takes place within what might be characterized as an innovation network: innovators with different interests loosely bound by common interests in the subject area, but distinguished by different aims. Partnerships are a form of network and as such help to expedite innovation. Given the complex nature of innovation, they are probably essential. Even so, true commercial partnerships are hard to find. Several instances of commercial partnerships are present in this collection, including the land satellite program, the Orbital Sciences case, X-33, and COTS. Some were successful in fostering innovation; others less so. The X-33/VentureStar history shows how an industrial party engaged in a partnership that NASA hoped would turn into a lasting relationship treated the arrangement as a bond that persisted only so long as the government kept paying most of the bills.

Third, partnerships come in many forms and are as old as the space program. Moreover, no two partnerships are identical. Take the examples of Ariel 1 in Chap. 2 and satellite telecommunications in Chap. 3. Ariel 1 was the first international cooperative project for the recently created NASA. The project was launched in 1962. It established the manner in which most bilateral programs have been carried out since that time; its importance as a path-marking effort is undeniable. The partnership established a precedent that long held implications for NASA's international programs, but no program was a duplicate of another. Likewise, the development of satellite communications represented an entirely different type of public/private partnership. The accompanying delay perhaps forestalled fruitful innovation, and only with the later establishment of a partnership did an industry that observers anticipated successfully begin operation. The potential for partnership was great, but was not effectively realized until the COMSAT Corporation began operations in the mid-1960s.

Fourth, competition encourages innovation. While government-granted monopolies may be useful for delivering certain services and protecting infant industries, they are not as effective as markets for promoting innovation and commercialization. Prime examples include the LANDSAT remote sensing system, the early satellite telecommunication efforts, the story of Orbital Sciences Corporation, and the Commercial Orbital Transportation System. LANDSAT, begun as a government program, was successful in establishing a technological process for acquiring orbital imagery of broad swaths of the Earth, but it was unable to operate in a self-sustaining manner and went through a broad array of institutional structures. Not until competition from private-sector firms arose in the 1990s did the system realize anything approaching its envisioned potential. Many government policy-makers sought to prohibit AT&T's US telecommunications monopoly from being extended to space, in part because of the stagnation in technology that monopoly practices allowed, but also because of the nature of this technology as a perceived public good. The rise of Orbital in the 1980s shows how NASA supported the effort by granting proprietary status, but with the intention that competition among more launch providers would be a benefit for Americans. Recent efforts to spread funds among several private firms seeking to advance space-access technology for low-Earth orbit also exhibit a belief in the value of competition.

Fifth, innovation is different than commercialization. One may make the case that LANDSAT, the space shuttle, and the X-33 development programs pursued innovative strategies, yet they never became cost-effective commercial activities. Government bodies often undertake activities with innovation potential for reasons other than profitability (prestige, wonder, imagination, privilege). Such activities are hard to commercialize, especially when they have the characteristics of public goods. The risks involved in commercializing new technologies increase with the ability of innovation proponents to deny reality, a major component of both the LANDSAT and space shuttle launch services pricing policy.

Sixth, innovation does not necessarily need to produce something new. It may consist of a clever reuse of old objects (repurposing). NASA officials used old technologies in creative ways in both the Skylab and Apollo–Soyuz projects.

Finally, while government bodies may foster innovation, the process is hard to maintain and institutionalize once underway, especially within units that grow more adverse to risk with time. A prime example of this is the Discovery program, operated by NASA's Office of Space Science. Originated in the 1990s, it has been generally successful, but over time the costs allowed have become greater and the risks accepted have become less.

Collectively, the chapters in this volume present new investigations into major episodes from NASA's past, each constructed to highlight the patterns of innovation that took place within their confines. Some of these episodes were enormously effective; others less so. All represented attempts to innovate in some fashion. Each enriches our understanding of this element of the history and legacy of expeditions into the unknown.

Notes

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14. Conservatives like Ridley and Kealey use this observation to disparage the value of government investment in basic research. In so doing, they confuse linear sequencing with knowledge growth. Basic research may not lead in a sequential fashion to new products, but it frequently enhances the basic science that explains how technology works. In that sense, investments in basic research can be said to produce more basic research. Beyond that, the discovery process can be tortuously complex. Hence, the consequences of research (more understanding) may be an effect as well as a cause of technology.

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