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Mission to Mars (A)

Firouz Naderi, the newly appointed Mars program manager, looked up from his chair to the photos of Mars that adorned the conference room wall. The photos from the Mars Global Surveyor expedition had stunned the scientific world, with pictures of what looked like natural gullies cut by water, perhaps 1 million or 2 million years ago or perhaps as recently as yesterday. Where there is water, there is usually a good chance of life, he mused.

But today, on a warm and sunny afternoon in the spring of 2000, Naderi had other things on his mind. He was meeting with Frank Jordan, program manager for Advanced Studies, and Chris Jones, director, Planetary Flight Projects, to discuss the future of the Mars exploration program. A few months earlier, NASA had been stunned by the loss of the Mars Polar Lander (MPL) spacecraft just minutes before it was due to touch down on the planet. It was the second mission failure in 10 weeks, coming on the heels of the loss of the Mars Climate Orbiter (MCO) in September 1999. As a result, Naderi, Jordan, and Jones faced some tough decisions.

Their most immediate concern surrounded the two missions that were in development for launch in 12 months. The two spacecraft—an orbiter and a lander—were being developed using the same "faster, better, cheaper" philosophy that had been used for both MPL and MCO. Furthermore, the designs of the 2001 craft used many of the same components as the 1998 craft. Given these risks, NASA had to decide whether to recommend proceeding with the development of both spacecraft, whether to cancel one and devote extra resources to the other, or whether to cancel them both. Given both had already reached the construction stage, it would be a difficult decision.

In addition to deciding the fate of the 2001 missions, the group faced a potentially more critical issue: the need to develop a long-term plan for Mars exploration that would stand the test of time. This would require assessing the appropriate scope and objectives for individual missions, as well as defining how these missions should be integrated into a coherent program. Naderi remarked:

> It seems like we need to draw up a new 10-year plan every 12 months. New discoveries, technological breakthroughs or technologies that don't pan out, changes in international partnerships, missions that do not succeed, budget changes and political pressures—there are so many risks and uncertainties that we face. It feels like we're always in a reactive mode, rather than a proactive one. We need to do some major rethinking of how to build flexibility into the program. Perhaps it's time to think about the problem in a completely different way.

Professor Alan MacCormack and Research Associate Jay Wynn prepared this case. HBS cases are developed solely as the basis for class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective management.

NASA and JPL: A Brief History[1]

"An Act to provide for research into the problems of flight within and outside the Earth's atmosphere, and for other purposes." With this simple preamble, the Congress and the President of the United States created the National Aeronautics and Space Administration (NASA) on October 1, 1958. NASA's birth was directly related to the pressures of national defense. After World War II, the United States and the Soviet Union engaged in the Cold War, a broad contest over the ideologies and allegiances of the nonaligned nations. During this period, space exploration emerged as a major area of contest and became known as the space race. On October 4, 1957, the Soviets launched Sputnik 1, the world's first artificial satellite, precipitating a full-scale crisis. A direct result of this event, NASA began operations less than one year later.

NASA absorbed the earlier National Advisory Committee for Aeronautics: its 8,000 employees, an annual budget of $100 million, three major research laboratories—Langley Aeronautical Laboratory, Ames Aeronautical Laboratory, and Lewis Flight Propulsion Laboratory—and two smaller test facilities. It quickly incorporated other organizations into the new agency, notably the space science group of the Naval Research Laboratory in Maryland, the Army Ballistic Missile Agency in Alabama, and the Jet Propulsion Laboratory, which was managed for the army by the California Institute of Technology. Today, NASA has 10 such research centers around the country.

The Jet Propulsion Laboratory[2]

The Jet Propulsion Laboratory (JPL) was a federally funded research and development center managed by the California Institute of Technology (Caltech). JPL's history dated to the 1930s, when Caltech professor Theodore von Karman conducted pioneering research in rocket propulsion. Von Karman, head of Caltech's Guggenheim Aeronautical Laboratory, gathered with several graduate students to test early rocket engines in a wilderness area in the Arroyo Seco, a dry canyon wash north of Pasadena, California. This area would become the home of JPL.

Von Karman received funding from the army during World War II to analyze the German V-2 program. From the early 1940s through the late 1950s, this growing research establishment—dubbed the "Jet Propulsion Laboratory"—received support from the U.S. military to develop not only rocket engines but other technologies necessary to guide and control missiles in flight. JPL made a large contribution to the flight and ground systems used in the first successful U.S. space mission, Explorer I. Twelve months later, in December 1958, it was transferred from army jurisdiction to the new civilian space agency, NASA.

JPL became NASA's center of excellence for planetary exploration as well as providing support for Earth-science and astrophysics missions (see **Exhibit 1** for JPL's mission history). During the 1960s, JPL managed NASA's Ranger and Surveyor missions to the moon in preparation for the Apollo lunar landings. From the late 1960s through the 1970s, JPL managed the Mariner missions, which explored Mercury, Venus, and Mars. It also assisted in the development of the two Pioneer spacecraft that traveled to Jupiter and Saturn. In 1975, NASA launched the Viking missions to explore Mars in greater detail, using two orbiters built by JPL and two landers that landed on the surface in July 1976. In 1977, JPL's Voyager 1 and 2 spacecraft were launched on a mission to the planets Jupiter and Saturn. Voyager 2 went on to fly by Uranus and Neptune, and both spacecraft

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[1] Source: Stephen Garber and Roger Launius, "NASA History Fact Sheet: A Brief History of the National Aeronautics and Space Administration," NASA Office of Policy and Plans, <http://www.hq.nasa.gov/office/pao/History/factsheet.htm>.

[2] Source: "NASA Facts: Jet Propulsion Laboratory," August 2001, <http://www.jpl.nasa.gov/about_JPL/facts/jpl.pdf>.

were expected to continue operating until the year 2020 billions of miles past the boundaries of our solar system. In 1989 and 1990, NASA launched three JPL missions on board the Space Shuttle: Magellan to Venus, Galileo to Jupiter, and Ulysses to study the sun's poles. All three spacecraft successfully completed their primary missions, and Galileo and Ulysses continued operating in an extended-science phase into the 21st century.

Organizationally, JPL utilized a matrix-type structure that allowed it to share expertise across different projects and programs as required. Divisions such as navigation, guidance and control, propulsion, and communications were repositories for knowledge and expertise, and projects were staffed through the allocation of engineers, specialists, and managers from the necessary divisions. Technical personnel reported to both a division manager and a project manager, allowing them to leverage their expertise across a variety of missions over time. On a typical project, only the most senior managers were colocated, while staff working within each division carried out the work.

Mission to Mars

> *Because of the way the planets line up, and given today's propulsion technology, there is an opportunity to fly to Mars only once every 26 months. Each time, you have a window of three weeks to launch a mission. If you miss it, you have to wait another 26 months. On top of that, you have to realize that it takes about four to six years to develop a mission to Mars. So those are the two main variables that dictate what we can do. And it's not easy. Between the Russians and the Americans, there have been approximately 30 missions to Mars to date, and two-thirds of these have failed completely or partly [see* ***Exhibit 2****]. Of the 12 attempts at landing on Mars, only three have fully succeeded. It really* is *rocket science.*
>
> —Firouz Naderi, Mars Program Manger

The Early Years[3]

Fascination with Mars began centuries ago. Its fiery color and erratic movement across the night sky terrified the ancient Greeks and Romans, causing them to name the planet after their gods of war. Giovanni Schiaperelli, an Italian astronomer, created a detailed gazetteer of the planet in the 19th century, using such beguiling names as Olympus and Elysium for the features he saw through his telescope. In 1877, Schiaperelli thought he saw streaks on the Martian surface and referred to them in his publications as canali, the Italian word for channels. This was, however, mistranslated into English as "canals," and theories of an inhabited Mars irrigated by melt waters from the polar ice caps began to flourish. Soon, the mere mention of the planet inspired visions of foreign worlds and fears of alien invasion. It became the subject of countless science-fiction tales.

It was to everybody's disappointment, therefore, that Mariner 4, the first probe to fly past Mars in 1965, revealed a surface that appeared to have been static for billions of years (see **Exhibit 3** for a gallery of U.S. Mars spacecraft). The atmosphere was thin, dry, and mostly of carbon dioxide. There were no canals, no little green men, no signs of life whatsoever. But a later mission, Mariner 9, showed in 1971 that the surface had extensive sand dunes, massive craters, and huge lava flows. Best of all, the probe found that although Schiaperelli's canali were indeed an artifact of his telescope, the planet did have canyons and networks of valleys that might have been carved by water flows sometime in the past. The evidence of water was exciting, for with it came the possibility of life.

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[3] This section is based on a description from *The Economist*, April 7, 2001, pp. 85–88.

The Viking Mission[4]

The early missions to Mars culminated in 1975 with the Viking program, a $1 billion project (over $4 billion in 2000 dollars) to send two spacecraft to the planet. Each spacecraft consisted of an orbiter, which would circle the planet, and a lander, which would travel to the surface. The two were attached for the year-long journey to Mars. Upon arrival, the orbiters began taking pictures of the Martian surface, from which a landing site was selected. The landers then separated from the orbiters, using retro-rockets to land softly. The orbiters continued imaging and, between the two of them, the entire planet was imaged at what was then high resolution. They also conducted atmospheric water vapor measurements and infrared thermal mapping. The landers took pictures (see **Exhibit 4**), collected and analyzed soil samples, and gathered data on temperature and winds.

The primary aim of the Viking missions was to look for any evidence of life, current or past, in the Martian soil. The payload aboard the landers therefore consisted primarily of biological experiments that were conducted on the samples dug by a small shovel. Unfortunately, the analysis of the soil showed them to be rich in iron but devoid of any signs of life. Naderi remarked: "The agency bet the farm on finding life with Viking. While in many ways it was a huge success, the problem was that it failed to find evidence of life. So as far as the public was concerned, there was little need to send anything that way again for a while. It was nearly 15 years before anyone suggested we pay attention to Mars again."

Mars Observer

Mars Observer (MO), launched in 1992, 17 years after Viking, was designed to study the geoscience and climatology of Mars, making observations over a two-year period. After nearly two decades without a Mars mission, the scientific community was eager to send a wide array of instruments to the planet. Development costs for the orbiter and its eight instruments hit $479 million, with an additional $293 million for the Titan launch vehicle and ground operations and $41 million for mission operations and data analysis—a total of $813 million ($1.13 billion in 2000 dollars). Donna Shirley, a manager on the subsequent Pathfinder mission, recalled:

> MO was a magnificent mission in the grand old style. At a cost of nearly a billion . . . it was designed to furnish more data than any scientist could analyze in a lifetime. It had a $22 million camera capable of taking thousands of high-resolution images a day, a laser altimeter to build a Martian topographical map, gamma ray and thermal emission spectrometers for geological content and history as well as instruments to measure Mars' magnetic field and gravity. All those scientific hopes and dreams were riding on that spacecraft.[5]

MO was launched in September 1992. On August 21, 1993, three days before the spacecraft was set to fire its main rocket engines and decelerate into orbit, flight controllers at JPL lost contact with the craft. The spacecraft was about to begin pressurizing its fuel tanks in preparation for the orbital insertion maneuver. A failure review board reported:

> Because the telemetry transmitted from the Observer had been commanded off and subsequent efforts to communicate with the spacecraft failed, the board was unable to find conclusive evidence pointing to a particular event that caused the loss of the Observer.

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[4] Viking overview taken from public information posted on the JPL Web site (updated April 11, 2002), <http://sse.jpl.nasa.gov/missions/mars_missns/mars-v1.html>, < http://www.jpl.nasa.gov/facts/viking.pdf>.

[5] Donna Shirley and Dannelle Morton, *Managing Martians* (New York: Broadway Books, 1998), p. 187.

> However, after conducting extensive analysis, the board reported that the most probable cause of the loss of communications with the spacecraft . . . was a rupture of the fuel [monomethyl hydrazine (MMH)] pressurization side of the spacecraft's propulsion system, resulting in a pressurized leak of both helium gas and liquid MMH under the spacecraft's thermal blanket.[6]

More than a decade of preparation, not to mention nearly $1 billion in taxpayers' money, was lost when the spacecraft disappeared.

Return to Mars: Faster, Better, Cheaper

On September 1, 1993, NASA Administrator Dan Goldin, in office for just over a year, announced that a study team led by Dr. Charles Elachi at JPL would explore a return mission to Mars. Goldin pushed Elachi to study creative ways to achieve the MO science objectives with a series of smaller missions, each with lower cost. This effort came to embody NASA's first foray into a philosophy known as "faster, better, cheaper" (FBC). It was a paradigm shift that would fundamentally change the way that NASA did business, affecting programs, projects, and missions for years to come.

Goldin had been chosen by President George Bush in early 1992 to replace Admiral Richard Truly as NASA administrator. In the late 1980s Bush had called on NASA to develop a plan for returning to the moon and moving onward with a human expedition to Mars. NASA's response was a series of proposals that would have cost tens or even hundreds of billions of dollars, far beyond the resources available to the agency at the time. In frustration, Mark Albrecht, staff director for the White House National Space Council, published an article in 1990 calling for new management approaches at NASA, specifically stating that "the basic goal is to do things faster, cheaper, safer, better."[7] When conflicts concerning this new paradigm arose with Truly, the Space Council decided to replace him with someone who could champion the new philosophy. Goldin had been a senior executive with TRW and had worked extensively on the Reagan administration's Strategic Defense Initiative "Brilliant Pebbles" project (a prototype ballistic missile defense system), which had sought to implement a "faster, better, cheaper" management style. His mandate for wholesale change at NASA was given impetus by the failure of Mars Observer, which followed hot on the heels of the embarrassing problems with the multibillion dollar Hubble Space Telescope's lens.

The fundamental tenets of FBC were laid out by Goldin in a speech in the fall of 1992:

> We should send a series of small and medium-sized robotic spacecraft to all the planets and major moons, as well as some asteroids and comets. Let's see how many we can build that weigh hundreds, not thousands, of pounds; that use cutting-edge technology, not 10-year-old technology that plays it safe; that cost tens and hundreds of millions, not billions; and take months and years, not decades, to build and arrive at their destination. Slice through the Gordian knot of big, expensive spacecraft that take forever to finish. By building them assembly line style, we can launch lots of them, so if we lose a few due to the riskier nature of high technology, it won't be the scientific disaster or blow to national prestige that it is when you pile everything on one probe and launch it every ten years.[8]

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[6] < http://klabs.org/richcontent/Reports/Failure_Reports/MarsObserverFailureSummary.htm>, accessed February 3, 2003.

[7] Mark. J. Albrecht, "The Council's Strategy for Space," *Roll Call*, June 25, 1990, p. 14.

[8] H.E. McCurdy, *Faster, Better, Cheaper: Low Cost Innovation in the US Space Program* (Baltimore, MD: Johns Hopkins University Press, 2001), pp. 50–51.

The FBC philosophy was first put into practice under the auspices of the Discovery Program, which was created in 1992. Concepts for Discovery missions were selected from bids made by universities, private research labs, NASA internal research teams, and industry. Guidelines for these missions included that the total development time could not exceed 36 months, development cost (from conception through launch) could not exceed $150 million, and operations costs (from booster separation through end of mission) could not exceed $35 million (all in 1992 dollars). Discovery missions had to be launched on board a Delta II rocket or smaller launch vehicle with a maximum launch cost of $55 million. *Aviation Week and Space Technology* explained, "Part of the Discovery Program's approach to lowering costs is to tolerate more risk and thus forgo some redundancies. For example, there will be no . . . ground spare to use if there is a launch failure." [9]

The new approach was also to become the cornerstone of the Mars Surveyor Program, a coordinated series of missions to explore Mars. The aim of the program was laid out in 1994:

> The Mars Surveyor Program has been developed as an aggressive but tightly cost-constrained program to explore Mars over the decade from 1997 through 2006. Small orbiters and landers built by industry will be launched at each of the opportunities, 26 months apart, afforded by the relative motion of Earth and Mars in their orbits around the sun. These multiple launches of small spacecraft will provide significant science return in a program that is not reliant on the success of any single component or mission.[10]

Managers at JPL were instructed to focus their efforts on smaller, less complex, but more frequent missions. How they did this, however, was left up to them. John McNamee, project manager for the Mars 1998 Climate Orbiter and Polar Lander missions, explained:

> People get the impression that headquarters passed out a manual with the details of how to run an FBC project, and that we received extensive training on how to implement it. The reality was that we were left to figure that out for ourselves, as long as we adhered to budget and schedule targets. The attitude was "the book is not working, so don't use the book—try something different, then write a *new* book." For the Mars program, we were given a development budget of $100 million a year [launch vehicle and mission operations costs were captured separately] and within this, the aim was to send both a lander *and* an orbiter at each opportunity, every two years. So we needed to build each spacecraft for $100 million. In addition, to save on launch costs, each had to ride atop a Delta rocket as opposed to a Titan, placing a limit on spacecraft size and weight.[11] Cost became the number one priority. If you exceeded your budget by 15%, the mission was subject to a cancellation review board.

Chris Jones, JPL Planetary Flight Projects director, reflected on the FBC paradigm shift:

> We were leaving the era of Viking, Voyager, Hubble, Mars Observer, Cassini[12]—missions that cost a billion or more and took decades to design, build, launch, and operate. By the early 1990s, the congressional budget process made it clear that those days were at an end. The "C" in FBC—cheaper—was coming whether we liked it or not. It was up to NASA, JPL, and our contractors to invent new procedures, new processes, and new ways of doing business that

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[9] *Aviation Week and Space Technology*, April 12, 1993, p. 52.

[10] Source: <http://mars.jpl.nasa.gov/mgs/pdf/010.PDF>, accessed February 10, 2003.

[11] Delta II launch vehicles carry between 1,500 and 3,800 pounds to orbit for around $50 million, compared with a Titan IV launch vehicle, which carries 8,600 pounds to the same orbit but costs upwards of $250 million.

[12] Cassini was a mission to explore the planet Saturn and its moons. The spacecraft was launched on October 15, 1997.

> would enable the "faster" and "better" portions. We rose to the challenge. Mars Pathfinder was our first opportunity to prove that this crazy idea could work.

Pathfinder Blazes the Trail

Pathfinder was originally planned as the first in a series of missions known as the Mars Environment Survey (MESUR), which would place up to 12 scientific monitoring stations at various locations across the Martian surface. In this role, it was being used to prove a number of different new technologies. In 1993, however, with MESUR losing favor among JPL's top brass, Pathfinder was designated a Discovery project and became subject to the strict cost and schedule requirements associated with that program. Tony Spear, a savvy and experienced JPL manager, was in charge of Pathfinder. But past experience was not necessarily going to help. As Brian Muirhead, Pathfinder's spacecraft manager, explained:

> The budget was less than the production cost of the movie *Waterworld*. We were being asked to do a major NASA mission for the cost of a Hollywood movie. "Well, at least our ending will be better," we joked. We also had to do the job in three years, which was about half the time of recent planetary mission developments. The 1976 Viking mission to Mars had taken seven years to develop.
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> These were impossible constraints. So it was clear that we'd have to throw the rule book away. But we'd been given license to do that. We began with the way we organized the team. We didn't really have the A-team available, given they were all on Cassini, so we knew we'd have to use younger, inexperienced people and make some radical changes in the way the team was organized. We decided to colocate about 100 people from different functional areas in one building. This was a complete change from the way JPL had operated in the past, where staff for a project would remain within their technical divisions and only see each other at meetings. It meant the different fiefdoms—for example, software and hardware—would have to communicate with each other personally, rather than just sharing documents. The team was also designed to be lean. At the peak, we had a total of around 330 people on Pathfinder, compared to 2,000 for Viking. We talked about being only "one deep," meaning there was only one specialist for each particular area. And we were big on individual responsibility—we made sure that every subsystem had a single owner.[13]

The constraints drove the need for significant amounts of innovation in the use of new technologies—Pathfinder developed and flew over 25 new or significantly reinvented technologies. Of these, the airbags used for landing attracted the most publicity. Muirhead continued:

> One of the first new things we decided on was to take the fast lane to Mars. There are a couple of ways to get there, but we followed the fast seven-month trajectory directly into the atmosphere of Mars at 16,400 miles per hour. This was the first time anybody had ever attempted to enter Mars' atmosphere directly [versus entering orbit first]. We really had to thread the needle to survive entry. We came up with two basic concepts for landing Pathfinder on the surface of Mars. One was a traditional approach—propulsive descent [using rockets]—just like Viking had done in 1976. The other concept was a wild idea—using giant airbags to cushion the lander's impact, then letting it bounce and roll to a stop. NASA basically looked at the two options and said, "Well, propulsion . . . that's the old way of doing business. You guys will never get this job done if you do it that way, it's too expensive."

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[13] Comments from Muirhead come from two sources: Price Pritchett and Brian Muirhead, *The Mars Pathfinder Approach to Faster-Better-Cheaper*, Pritchett & Associates, 1998; and an interview with Muirhead, December 13, 2001.

Pathfinder proposed to head straight into the atmosphere, slowing its descent first using the atmosphere (albeit the thin atmosphere), and then by parachute. Finally, the airbags would deploy before the craft hit the ground. Muirhead explained:

> What we needed would have to be about 19 feet in diameter, designed to tolerate a head-on collision with a very rocky Mars surface at 60 miles per hour or more. And not just once, but multiple times, as it bounced and rolled to a stop. . . . This job took a lot of trial and error. Tom [Rivellini, airbag systems manager] started with a 1/20th scale model, and worked up to full scale. . . . Our first drops on a rocky surface simulating expected Martian terrain were complete failures. We weren't sure if this thing was going to work. But we kept working the details, improving the design, and going back in to test. It was a very iterative process. We tried an analytical approach, but we spent over a week of Cray computer time to get only a few seconds of data on the impact. The problem was just too complex. . . . So we had to rely on Tom and his team's ability to design, build, and test their way to a design that would work.

Pathfinder comprised both a spacecraft and an independent rover called "Sojourner," which would explore the surface after landing. Shirley, who led the 30-person rover team, recalled:

> Many of us, myself included, had never delivered flight hardware, the touchstone of competence at JPL. If you've never sent a piece of hardware up into space, then no one believes you could ever do that job. It was a classic catch-22 situation that had dogged my professional career for years. . . . JPL's flight director . . . brought in a hard-bitten group of senior mission veterans he called the "Red Team" to review the project. . . . The Red Team was a distinguished bunch, 12 people, most of them with 25 years of experience building flight hardware. . . . Led by Jim Martin, the former Viking project manager, it was loaded with former Viking people, all of whom believed it was impossible to land on Mars as cheaply as we were attempting. . . . Instead of the normal two or three reviews, Pathfinder had about 25 reviews in a two-year period.
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> Our only hope for meeting the mass, cost, and power limits was to show the review board how we would do things differently from the way anyone had ever done them before. For example, adapting commercial motors to power the wheels was on the face of it a cheaper solution than building and testing motors of our own design [see **Exhibit 5**]. . . . We weren't going to spend millions on flight-qualified radios, but hundreds of thousands on commercial radio modems. As for cameras, we were going to make our own out of a few chips and connectors. . . . For some of the electronics and controls, Henry Stone [manager for the rover's control and navigation subsystem] had suggested that we could buy spare electronics parts from Cassini, which was finishing up its design phase.[14]

Muirhead emphasized that what the Pathfinder team did was not "normal" practice at JPL:

> What we were doing was completely countercultural. We were a band of rebels and renegades. In that respect, we probably scared upper management [at JPL]. What we were doing didn't fit any of the old models about how to run a project—people claimed we didn't have enough rigor or hierarchy. It almost seemed as if some people wanted us to fail. And even when we succeeded, there were those who thought that we hadn't proven anything. That it must have been an anomaly. The fact that it was a Discovery mission and not part of the formal Mars Surveyor Program established in 1994 probably contributed to this tension.

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[14] Shirley and Morton, pp. 166–167.

Pathfinder was launched in December 1996. The project had stayed on budget, coming in at a total cost of $265 million, including development ($170 million for the lander and $25 million for the rover), launch ($50 million), and mission operations ($20 million). On July 4, 1997, the spacecraft hit the Martian surface at 31 miles per hour. It bounced 15 times, as high as 50 feet, before coming to rest more than two minutes later about a kilometer from the point of initial impact.

As the airbags began to retract into the lander, however, there was a problem—one that had fortunately been anticipated during ground tests. As Muirhead explained:

> People always asked at reviews, "You guys had to cut corners, didn't you?" And we'd tell them, "No, we actually added tests." That's typically where missions run into trouble. They run out of time and/or money, so they begin cutting out tests, the only thing left to cut. But we didn't. We knew testing was key to our success and found ways to keep testing, right up to landing day. . . . Robustness and demonstrated margin were key to the success of a design that was basically a "single-string" spacecraft. For most elements of the spacecraft, we were one resistor, one transistor, one integrated circuit, one mechanical device away from . . . disaster.
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> We simulated the entire entry condition and the landing. And then all the operations on the surface. . . . To help us test, we built a giant sandbox with sand and rocks to simulate the Mars terrain. . . . David Gruel, a 27-year-old engineer, was assigned to be the project's "gremlin." . . . He set up problem situations in the sandbox that the team had to figure out how to overcome. . . . The value of this planning and testing showed up on the first day on Mars. One of the problem scenarios the gremlin had posed for us had the airbags draped over the lander petal, preventing the rover from driving off. We'd figured out how to fix that problem in our earthbound sandbox by lifting up a petal and pulling the airbag in further. When we saw this same problem in our first images from Mars, we knew exactly how to handle it.

Indeed, "test, test, test" had been manager Spear's mantra since the beginning of the project.[15] To leave time for testing, Spear had insisted that contractors and subsystem managers deliver their hardware no later than halfway through the development cycle. This was a demanding requirement, given the development cycle was already substantially shorter than those of previous missions due to the limitations established when Pathfinder became part of the Discovery Program.

On July 5, the Sojourner rover rolled down the lander's ramp to the Martian surface. Using its primary scientific instrument, an alpha proton X-ray spectrometer, the rover was able to assess the chemical composition of the Martian soil and rocks in the landing area.[16] The lander and rover continued functioning until late September, providing spectacular images of the Martian surface (see **Exhibit 6**). It received tremendous media coverage, with the project Web site becoming for a short period the most trafficked site on the Internet, generating 450 million hits in 30 days.

Interest in Pathfinder had been bolstered by the discovery of what appeared to be microbial fossils in a meteorite from Mars the previous summer. The meteorite was recovered in Antarctica, where it had landed more than 13,000 years ago having been ejected from Mars by an asteroid impact millions of years earlier. Although it was not proven that the anomalies in the meteorite were fossils, the excitement in the scientific community was palpable. In August 1996, Goldin beamed ". . . we have 10 spacecraft scheduled to go to Mars in the next 10 years. . . . We'll see results year after year and the American people will share it with us."[17] With the impetus generated by Pathfinder's success and the

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[15] McCurdy, p. 130.

[16] Pathfinder carried very little in the way of scientific instruments, given its heritage as a technology demonstration mission.

[17] "NASA to revise space missions to focus on Mars findings," CNN Interactive, Jim Slade & AP contributions, August 7, 1996.

possibility of life on the red planet, Congress granted NASA additional funds, increasing the Mars exploration budget from $150 million per year in 1995 to $250 million per year by 2000. In return, NASA took on the challenging goal of returning a soil sample from Mars to Earth by 2008.

Mars Global Surveyor: Recovering from Mars Observer

As Pathfinder was finishing its duties on the surface, a second spacecraft, Mars Global Surveyor (MGS), entered orbit around the planet with a mission to map the surface in greater detail than ever before. As the first official mission in the Mars Surveyor Program, MGS had a charter to capture the science objectives from the failed Mars Observer mission. In November 1996, the orbiter was launched, carrying duplicates of five Mars Observer instruments plus additional communications equipment to relay data back to earth from subsequent landers. It arrived at Mars in September 1997 ready to use its large solar panels to provide drag in the Martian atmosphere, slowing the spacecraft in a maneuver known as "aerobraking." Tom Thorpe, MGS operations project manager, recalled:

> We were all set for an elegant aerobraking maneuver that would eventually settle the spacecraft into a nice circular orbit. This helped keep us under our project budget by lowering the amount of fuel we needed to carry for maneuvering and orbital insertion [MGS carried less than 700 pounds of fuel, compared with the 3,175 pounds carried by Mars Observer]. But we discovered a structural problem with one of the solar panels on the spacecraft, so we had to modify our trajectory to ensure that the weakened panel didn't get overstressed. With this more cautious approach, the aerobraking maneuver would take a year longer than originally planned.

MGS came in 8% under budget with a development cost of $131 million, an additional $53 million in launch costs, and $90 million for mission operations. The spacecraft began its primary mapping mission in March 1999, returning a fantastic array of detailed photos of the Martian surface.

Mars 1998: Mars Climate Orbiter and Mars Polar Lander

The Mars 1998 missions began in 1995. The aim was to develop both an orbiter and a lander for a development cost (excluding launch and operations) of $100 million each. Given these costs were almost half those of Pathfinder, the team could not just "knock off" Pathfinder's design. However, it was able to borrow its aeroshell design and spare parachute and secured spare microprocessors and radio equipment from the Cassini program. The contract for construction of both the orbiter and lander was awarded through a competitive bidding process. In March 1995, Lockheed Martin Astronautics won the bidding for both and began a cooperative effort with JPL to design and build the spacecraft. McNamee, project manager for the Mars 1998 missions, recalled:

> In line with FBC, the request for proposal for the two missions was only 30 pages long, rather than thousands. Lockheed bid $85 million for *both* spacecraft. Our financial people told them that this wasn't enough, so we agreed to pay for any overruns. The way they'd got the cost down so much was that they were leveraging a bunch of people across several projects—it was a classic matrix organization. For example, their attitude control guy [responsible for the electronics and software that govern the way the spacecraft flies] was leading a project called "Stardust" in addition to our two missions. Plus they were also using a lot of common systems between the two spacecraft. We oversaw development with a team of 10–15 at JPL plus some additional specialists on their site in Colorado. But in reality, Lockheed was given a lot of independence. At one point, I asked for another $20 million to supervise the project, but given this didn't seem to be in line with FBC, we didn't get it.

The Science Definition Team at NASA had issued the "announcement of opportunity" for the 1998 missions in January 1995, with interface specifications for the lander and orbiter (specifying power, mass, volume, data rate, etc.). Teams of scientists from industry, government, and academia were invited to propose instruments to ride on the missions. The final selections were made in November 1995, one month before construction was due to begin. Shortly after, however, headquarters decided to invite the Russians to participate, adding a laser detection and ranging instrument in January 1996. The following month, a push from the New Millennium office—a program for testing new space technologies—led to the addition of two "Deep Space 2" probes, ground-penetrating instruments designed to be dropped from the lander during entry. Finally, a lobbying effort by Carl Sagan and the Planetary Society led to the addition of a microphone in September 1996 so we could listen to the sounds of Mars for the first time. McNamee, in charge of delivering flight hardware for the first time, recalled, "They gave us the extra budget to fly each of these things, but the launch window was fixed, so there was just more stuff to do."

Mars: The Bringer of War

After completing its nine and a half month voyage to Mars, MCO fired its main engine at 2 p.m. (PDT) on September 23, 1999, to begin orbital insertion. The burn began as planned five minutes before the spacecraft passed behind Mars, but flight controllers did not detect a signal when the spacecraft was expected to come out from behind the planet. Through a review of navigation data sent by the craft, the team at JPL was able to determine that the orbiter had approached the planet at an altitude of just 37 miles, 56 miles lower than intended, causing the spacecraft to burn up in the atmosphere and crash to the surface. By September 30, the preliminary findings indicated the problem resulted from an error in critical navigation calculations. All values were supposed to have been reported by the Lockheed Martin team to JPL in metric units, but some were provided in English/imperial units. The failure investigation board noted in November 1999:

> The root cause of the loss of the spacecraft was the failed translation of English units into metric units in a segment of ground-based, navigation-related mission software. . . . The failure review board has [also] identified other significant factors that allowed this error to be born, and then let it linger and propagate to the point where it resulted in a major error in our understanding of the spacecraft's path as it approached Mars.[18]

On December 3, 1999, Polar Lander arrived at Mars on a perfect trajectory. The spacecraft entered a brief period of communications blackout during descent, but contact was never regained. Assessing the cause of failure was made difficult by the absence of telemetry data on entry, descent, and landing conditions, a $4 million transmitter that could have provided such data deemed an unnecessary expense in the era of FBC. However, a failure review board later determined that the lander had most likely crashed to the surface due to a premature shutdown of its main engine, used to slow the descent. The engine was programmed to cut off upon landing, as determined by the deceleration force of impact with the surface. This would prevent the spacecraft from overturning if the engine continued to burn after landing. Unfortunately, the deployment of the spacecraft's three legs, 130 feet above the surface, generated a deceleration force similar in nature to that experienced upon landing. The computers controlling the engine interpreted the jolt from the legs deploying as the force of landing and shut down the main engine. The spacecraft fell the last 130 feet to the surface, destroying the lander. McNamee recalled:

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[18] Source: <http://mars.jpl.nasa.gov/msp98/news/mco991110.html>, accessed February 10, 2003.

> We had tested the spacecraft's landing mode—the firing of the retro-rockets, touchdown on the surface, and propulsion shutdown upon contact. But we hadn't tested the full, continuous landing sequence, from entering the atmosphere to touchdown, which would have included deploying the legs. Budgets were tight so choices had to be made as to what to test. It's incredibly unfortunate that the full-sequence test was one of the tests that didn't make it.
>
> I went with my resignation and told Dan Goldin that I accepted full responsibility for the failures. He wouldn't have it. He was furious about the situation, but his anger wasn't directed at me. Faster, better, cheaper was a fine idea that had been pushed too far. In the end, it was probably going to be a simple error that got us—a "one" when a "zero" should have been there, a positive instead of a negative. And we were so lean that there's no one else to catch it. With single specialists on each subsystem, there is no one else to bounce ideas off. Couple that with the fact that most engineers worked 80-hour weeks for months on end. If there was a failure, it was not recognizing how we were stressing the team.

The Aftermath of Mars 1998

The impact of the failures was dramatic. Multiple failure boards were convened at NASA, JPL, and Lockheed Martin. The NASA FBC Task Force led by Spear concluded in March 2000:

> FBC is *not* trying to fit a challenging mission scope within arbitrary schedule and cost caps. For the first generation of FBC projects, mission scope fit fairly well within the caps, that is, for Clementine [a lunar probe], Near Earth Asteroid Rendezvous, Mars Pathfinder, Mars Global Surveyor, Lunar Prospector, and Stardust, for example. However, in our zeal to do FBC and in learning to do programs at the NASA centers, the challenge bar was raised too high for some of the second-generation missions. The cost-cap challenges were made too great, along with a mix of unstable funding and escalating requirements.[19] [See **Exhibit 7** for development cost data on selected planetary missions.]

Naderi explained, "After Pathfinder, we kind of said, 'If a little cheaper is good, then a lot cheaper must be better.' It was like being in the Olympic high jump—you never quit on a success. We were going to keep raising the bar, and eventually, you knew what would happen." Others in the organization emphasized that there was not that much of a gulf between success and failure. As McNamee pointed out, "Pathfinder itself almost failed three or four times, but you don't hear about that, because there are no postmortems on successes."

As the provider of funds for all NASA programs, Congress demanded to know what had happened. Goldin was called before the House Science Committee. He explained:

> Although the Mars 1998 projects may be dramatic examples of processes and practices applied with insufficient rigor, they do not represent the norm for NASA projects. The Mars 1998 schedule demands were unrelenting, the science demands substantial, and the cost demands aggressive. The combination of these constraints, and the inability to identify, communicate, and mitigate the unacceptably high risk they posed, manifested itself as mission failures. . . . Managers at JPL and [Lockheed Martin] tended to focus on cost and schedule and used increased risk as a relief valve . . . because the individual projects were not integrated into a whole program; each mission looked after its own communications needs, navigation requirements, and technology investment. This resulted in a fragmented program without a

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[19] Source: <http://appl.nasa.gov/resources/FBCspear.pdf>, accessed February 3, 2003.

> fully integrated, clear, and cohesive strategy. . . . There was no single individual responsible for the Mars program at NASA headquarters or JPL.[20]

To address communication, or miscommunications, that had contributed to the problems between headquarters and JPL, two key appointments were made. Goldin announced the appointment of Scott Hubbard as the Mars program director at NASA headquarters. To match this change, JPL formed a Mars Program Office and appointed Naderi as program manager reporting directly to the JPL director. Naderi would become the single point of contact for headquarters, with an unambiguous, formal line going from the headquarters program director to the JPL program manager. Top-level policies would be issued by the program director, and the program manager would have full end-to-end responsibility for implementing the program. These two appointments provided the backbone for the new management organization and cleaned up the confusion in directing and reporting between headquarters and JPL.

A series of process changes were also implemented to strengthen career development programs for project managers, stressing the importance of identifying, evaluating, and documenting options for mission-critical decisions. Revisions were made to processes used for verification and validation, risk management, and configuration management. Implementation processes were revised to ensure the early application of systems engineering principles and the establishment of robust design margins. The JPL Systems Management Office was tasked to conduct risk assessments for all projects, and JPL's Governing Program Management Council was given authority to evaluate each major project's implementation plan and readiness to proceed. Finally, a series of initiatives were implemented to improve NASA's ability to share lessons learned across completed projects.[21] This was no easy task. As Shirley noted when Pathfinder's mission was coming to a close: "The Pathfinder team, much in demand as the people with the Better Faster Cheaper know-how, had already largely scattered to other projects. . . . I had to nag them to document their lessons learned before they disappeared. . . . When most projects were over, the detailed lore of how they were done was usually only in people's heads."[22]

Rebuilding the Mars Program

The impact of the Mars 1998 failures resonated through the halls of JPL for many months after the events had transpired. While Pathfinder had seemingly shown that an FBC approach could be successful, two failures in a row had been a major blow to its supporters. Adding to the gloom, several other missions run under the mantra of FBC had also met with failure (see **Exhibit 8**). Yet was not this precisely the risk that FBC involved embracing? Jordan reflected:

> The problem is we are in a fishbowl. People said, "Let's take more risk, do more smaller missions and accept that there will be some failures, as long as we learn from them." But lose $200 million, and they go "gulp, that wasn't meant to happen." Many people at JPL thought we could have continued the Mars program from a *technical* perspective after the 1998 failures—but politically, there was no way. Changes had to be made.

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[20] Source: <http://www.hq.nasa.gov/office/legaff/goldin6-20.html>, accessed February 3, 2003.

[21] NASA had developed an information system for capturing lessons learned in 1995; however, a 2001 survey of managers found that only 23% of respondents had ever contributed to this system, and 27% were not even aware of its existence.

[22] Shirley and Morton, p. 259.

But what should those changes involve? A move away from FBC, or a rededication to the philosophy with some minor tweaks? Around the halls of JPL, many project managers began to raise questions about the "more for less" approach. One explained:

> There is a reason that larger satellites have been favored in the past. If you are traveling a long way, you're already paying a lot to get there [see **Exhibit 9**]. For example, on an incremental basis, it wouldn't cost much to add one more experiment to the Europa[23] mission that's currently in development. The alternative is to wait until the next mission to Europa, but who knows when that will be? The way we look at it, our customers—people in the science community—have, at most, six chances in their lifetime to be part of a Mars mission. So if we can do something to help them out, we will.

Even Jordan was unconvinced that a Mars program consisting only of small, low-cost, Pathfinder-like missions could be viable longer term. He explained:

> Pathfinder worked because it was narrowly focused on a single objective. But it also stood on the shoulders of JPL's heritage in a big way. It didn't have to develop technologies like the navigation software because they could adapt software from previous missions. They adopted the aeroshell design [the system that stopped the spacecraft burning up as it entered the Mars atmosphere] and the parachute system used by Viking. Finally, they had the luxury of piggy-backing on the Cassini project for some of their parts.

Jordan continued:

> Cassini cost several billion and took seven years to develop before its launch in 1997. It paid for the development of a comprehensive testing infrastructure at JPL, which has been used by everyone since. Programs like Discovery and projects like Pathfinder worked because they had this huge beast to feed off. But how is that type of infrastructure going to be built in future? The Office of Space Science won't fund projects to build *only* infrastructure, so it has to be built inside projects. In essence, technical divisions charge more to large projects to build and maintain skills for *future* missions. At present, the only project we have like this is the $1 billion Europa orbiter, scheduled for launch in 2008. But we can't all live off its back.

The question of the appropriate size and scope of missions was closely related to the broader question of how to design an effective "program"—a plan that spanned a decade and connected multiple missions with interlinked capabilities and objectives. The aim was to make the whole greater than the sum of the parts. For example, it was more effective for an orbiter to relay signals from a Mars lander back to earth than to have the lander waste valuable payload weight carrying a transmitter powerful enough to send signals to earth independently. But this type of coordination was not easy to manage. Naderi explained:

> Project managers have always been the kings at JPL. They are the ones with the resources, the prestige, etc. If you ask them to do something on their mission to support the *next* mission, the reaction is not easy to predict. For example, we have always built our communications systems using the X-band [frequency]. But soon we will need to move to KA-band, given the greater amount of data we want to transmit. So we are leaning on a project manager to fly KA-band as an experiment. To do this, we offer to compensate them by allocating them the additional budget they will need to launch and fly it. But the project manager is understandably wary of the idea—no surprise, given that for years, we have told them to focus

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[23] Europa is a moon of Jupiter.

> only on optimizing their own mission. So the question is what *organizational* steps should we take to ensure this type of coordination happens effectively in future?

Naderi faced a potentially more significant challenge in building a program that was robust despite the many uncertainties that could affect it. The most obvious of these uncertainties was the risk of one or more missions failing—as sharply highlighted by the events of 1999. But there were many other uncertainties, many of which had nothing to do with the program itself. Naderi explained:

> There are a series of political constraints that stem from the fact that every four or eight years there is a change of administration. We need to give them something to show for their money. And each administration has different philosophies about how much and where they want to spend their money—for example, on manned versus unmanned missions. Then we have to be flexible about the possibility of international participation, which can be driven by factors that are unrelated to the program itself. Finally, we also have to deal with unforeseen events like 9/11, which although unrelated to NASA, are bound to result in a shake-up of budgetary priorities, some of which will ripple through to us.

There was also a need to be responsive to the scientific discoveries generated by each mission, which could change the priorities for future missions. The science objectives for the program were determined by the Mars Exploration Program Advisory Group (MEPAG), a group of academics whose job was to assess the value of various observations and outline the priorities at any point in time. But as Edward Weiler, NASA's associate administrator for space science, put it, "You have to assume Mars will continue to surprise us."[24] Hence the program had to be *flexible* enough to respond to the new information that each mission would generate. That was not easy, as Naderi explained:

> In terms of reacting to new discoveries, the main constraint is our existing technical capability. Take the MGS mission, which highlighted gullies that looked to have been formed by water. The first thing we ask ourselves is, "Can the next missions go to these areas?" Then we ask, "How could we get there?" These gullies were at the high latitudes and not easily accessible. Finally we ask, "What do we have to do when we get there?" In this case, the slopes of the gullies are greater than our existing spacecraft or rover designs can handle. Ultimately, these constraints dictate how responsive we can be to scientific discoveries. So the question is, "How can we ensure our *technical capability* continues to evolve, while simultaneously making sure we also continue to deliver results to the science community?"

Decisions

Naderi, Jordan, and Jones huddled in the conference room, a long afternoon ahead of them. Their immediate concern surrounded what to recommend be done about the upcoming 2001 missions, which involved an orbiter and a lander already under construction. The main risk was that these spacecraft were based upon the designs for the 1998 missions and had been developed to that point using the same FBC philosophy and by the same contractor—Lockheed Martin Astronautics. Yet both had also undergone significant evolutions and increases in scope during development, departing in many ways from the 1998 designs. For example, the design for the lander had evolved to include delivering a "rover" to the surface, boosting the payload to 66 kilograms, three times that of MPL's design, which had not included a rover. One program manager explained the reasons for such changes:

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[24] "A Mars Never Dreamed Of," *National Geographic*, February 2001.

> Each mission requires heavy optimization. The science community doesn't want to run the same experiments again, so the design tends to change significantly from mission to mission. We've just met this issue recently with the design of the rovers planned for 2003. We originally thought we'd just wrap up the new rovers in the old Pathfinder airbag and shoot them direct to Mars. But guess what—a rover that can do any new science [i.e., in comparison to what Sojourner achieved] proved to be too large for the old landing system. We needed costly and time-consuming design modifications.

By spring 2000, an extensive testing program had begun on the 2001 spacecraft. Indeed, it was during the testing of the lander in January 2000 that the team had discovered that deploying the legs could be interpreted as the jolt from landing, helping the MPL failure review board determine the most likely cause of its loss. While the design reviews conducted on each spacecraft tended to show they were ready to fly, the repercussions of another failure would be immense. So should they fly both spacecraft as planned, cancel one and divert money and resources to the other, or cancel both?

Naderi's team also had to address the critical issue of how to reconstruct the Mars program. This would involve assessing the appropriate frequency and scope of individual missions, ensuring that they would fit the budget for the program, projected to increase to over $300 million in 2001 (see **Exhibit 10**).[25] It would require developing solutions to the need for greater coordination within the program and enhanced flexibility in reacting to new discoveries. Finally, there was the issue of sample return. Since the 1996 discovery of the Mars meteorite in Antarctica, this had become a sort of Holy Grail for the program. But such a mission was not a natural extension of the measured-science approach that had been the initial aim of the Mars program. Jordan explained:

> To return a soil sample we have to land on the surface, have a rover go out and collect samples from multiple sites, transfer these to the lander, launch the samples into Mars orbit, rendezvous with an orbiter, transfer the samples to the orbiter, and bring the orbiter back to Earth. At least six major breakthrough technologies are needed for all this to work effectively. Such a mission will cost at least $1 billion, and probably closer to $2 billion.

Naderi reflected:

> All past evaluations of the science priorities for Mars have stressed the importance of sample return. However, the cost has always been an impediment. Furthermore, there is the question of how much prior survey work from orbit and *in situ* is needed to make sure we collect the right samples. Finally, some observers claim that sample return requires a return to the managerial approach used prior to faster, better, cheaper. It's our job to work out whether this should be the case or not.

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[25] This budget was to cover development costs, launch costs, mission operations costs, and data analysis costs (previously under a separate budget). Launch costs for Delta vehicles were projected at around $50 million. Mission operations costs typically ran at around $20 million to $40 million for landers/rovers and $50 million to $100 million for orbiters, reflecting the longer operating period of orbiters. Data analysis costs were projected at $30 million to $50 million per mission.

Exhibit 1 JPL's Spacecraft Mission History

Spacecraft, Launch Date, Mission Description, Comment

Explorer I, 1/31/58, first U.S. satellite, operated to 5/23/58

Explorer 2, 3/5/58, satellite, launch failed

Explorer 3, 3/26/58, satellite, operated to 6/16/58

Explorer 4, 7/26/58, satellite, operated to 10/6/58

Explorer 5, 8/24/58, satellite, launch failed

Pioneer 3, 12/6/58, escape attempt, in orbit to 12/7/58

Pioneer 4, 3/3/59, escaped to solar orbit, tracked to 650,000 km (400,000 mi)

Ranger 1, 8/23/61, lunar prototype, launch failure

Ranger 2, 11/18/61, lunar prototype, launch failure

Ranger 3, 1/26/62, lunar probe, spacecraft failed, missed moon

Ranger 4, 4/23/62, lunar probe, spacecraft failed, impact

Ranger 5, 10/18/62, lunar probe, spacecraft failed, missed

Ranger 6, 1/30/64, lunar probe, impact, cameras failed

Ranger 7, 7/28/64, lunar probe, successful, 4,308 pictures

Ranger 8, 2/17/65, lunar probe, successful, 7,317 pictures

Ranger 9, 3/21/65, lunar probe, successful, 5,814 pictures

Surveyor 1, 5/30/66, lunar lander, operated 6/2/66–1/7/67

Surveyor 2, 9/20/66, lunar lander, crashed 9/23

Surveyor 3, 4/17/67, lunar lander, operated 4/20–5/4/67

Surveyor 4, 7/14/67, lunar lander, crashed 7/17

Surveyor 5, 9/8/67, lunar lander, operated 9/11–12/17/67

Surveyor 6, 11/7/67, lunar lander, operated 11/10–12/14/67

Surveyor 7, 1/7/68, lunar lander, operated 1/10–2/21/68

Mariner 1, 7/22/62, Venus probe, launch failed

Mariner 2, 8/27/62, Venus flyby 12/14/62, signal lost 1/3/63

Mariner 3, 11/5/64, Mars probe, shroud failed

Mariner 4, 11/28/64, Mars flyby 7/14/65 with pictures, signa1 lost 12/20/67

Mariner 5, 6/14/67, Venus flyby 10/19/67

Mariner 6, 2/24/69, Mars flyby 7/31/69 with pictures, lasted to 12/70

Mariner 7, 3/27/69, Mars flyby 8/5/69 with pictures, lasted to 12/70

Mariner 8, 5/8/71, failed Mars launch

Mariner 9, 5/30/71, Mars orbiter 11/13/71–10/27/72

Mariner 10, 11/3/73, Venus swingby 2/5/74, Mercury 3/29, 9/21, 3/16/75

Viking 1, 8/20/75, Mars orbiter/lander, orbit 6/19/76, landing 7/20/76

Viking 2, 9/9/75, Mars orbiter/lander, orbit 8/7/76, landing 9/3/76

Voyager 1, 9/5/77, Jupiter 3/5/79, Saturn 11/12/80 with pictures, continues on interstellar mission

Voyager 2, 8/20/77, Jupiter 7/9/79, Saturn 8/25/81, Uranus 1/24/86, Neptune 8/25/89, continues on interstellar mission

Seasat, 6/27/78, ocean radar satellite, operated three months

Solar Mesosphere Explorer, 10/6/81, successful

Infrared Astronomical Satellite, 1/25/83, NASA/United Kingdom/Netherlands orbiting infrared telescope, operated to 11/23/83

Magellan, 5/4/89, Venus radar mapper, orbited 8/10/90–10/13/94, mapped 99% of planet

Galileo, 10/18/89, Jupiter orbiter/probe; Venus swingby 2/10/90, Earth swingby 12/8/90, asteroid Gaspra flyby 10/29/91, second Earth swingby 12/8/92, Ida flyby 8/28/93, Shoemaker-Levy observations 7/94, arrived at Jupiter 12/7/95 for two-year mission and accomplished atmospheric probe portion of mission; currently in extended mission focused on Jupiter's moons Europa and Io

Ulysses, 10/6/90, European Space Agency/NASA solar polar mission; Jupiter swingby 2/8/92, solar southern polar passage 6/94–11/94, northern passage mid-I995

Mars Observer, 10/25/92, lost at Mars orbit insertion (8/24/93)

Topex/Poseidon, 8/10/92, NASA/French ocean satellite, operating

Mars Global Surveyor, 11/7/96, entered Martian orbit 9/12/97, science mission begins 3/99

Mars Pathfinder, 12/4/96, landed 7/4/97 and deployed rover

Cassini, 10/15/97, Saturn orbiter with Huygens descent probe to study Saturn's moon Titan; Venus flybys 4/26/98 and 6/24/99, Earth flyby 8/18/99, Jupiter flyby 12/30/00, Saturn arrival 7/1/04, Huygens descent 11/27/04

Deep Space 1, 10/24/98, testing ion engine and 11 other advanced technologies; asteroid flyby 7/99, comet flyby planned 9/01

Mars Climate Orbiter, 12/11/98, lost during Mars arrival 9/23/99

Mars Polar Lander and Deep Space 2 microprobes, 1/3/99, lost during Mars arrival 12/3/99

Stardust, 2/7/99, en route to comet flyby 1/2/04, Earth return 1/15/06

Wide-field Infrared Explorer (WIRE), 3/4/99, telescope coolant lost shortly after launch

Quick Scatterometer (QuikScat), 6/19/99, ocean winds satellite, operating

Active Cavity Irradiance Monitor Satellite (AcrimSat), 12/20/99, Earth-orbiting satellite monitoring sun's radiation output

Source: <http://www.jpl.nasa.gov/about_JPL/facts/jpl.pdf>.

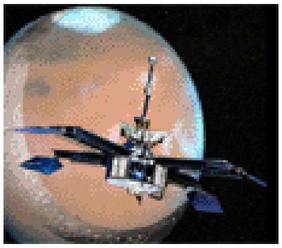
Exhibit 2 Mars Mission History

Mission	Country	Launch Date	Purpose	Results
[Unnamed]	USSR	10/10/1960	Mars flyby	Did not reach Earth orbit
[Unnamed]	USSR	10/14/1960	Mars flyby	Did not reach Earth orbit
[Unnamed]	USSR	10/24/1962	Mars flyby	Achieved Earth orbit only
Mars 1	USSR	11/1/1962	Mars flyby	Radio failed at 65.9 million miles (106 million km)
[Unnamed]	USSR	11/4/1962	Mars flyby	Achieved Earth orbit only
Mariner 3	U.S.	11/5/1964	Mars flyby	Shroud failed to jettison
Mariner 4	U.S.	11/28/1964	First successful Mars flyby 7/14/65	Returned 21 photos
Zond 2	USSR	11/30/1964	Mars flyby	Passed Mars but radio failed, returned no planetary data
Mariner 6	U.S.	2/24/1969	Mars flyby 7/31/69	Returned 75 photos
Mariner 7	U.S.	3/27/1969	Mars flyby 8/5/69	Returned 126 photos
Mariner 8	U.S.	5/8/1971	Mars orbiter	Failed during launch
Kosmos 419	USSR	5/10/1971	Mars lander	Achieved Earth orbit only
Mars 2	USSR	5/19/1971	Mars orbiter/lander arrived 11/27/71	No useful data
Mars 3	USSR	5/28/1971	Mars orbiter/lander, arrived 12/3/71	Some data and few photos
Mariner 9	U.S.	5/30/1971	Mars orbiter, in orbit 11/13/71 to 10/27/72	Returned 7,329 photos
Mars 4	USSR	7/21/1973	Failed Mars orbiter	Flew past Mars 2/10/74
Mars 5	USSR	7/25/1973	Mars orbiter, arrived 2/12/74	Lasted a few days
Mars 6	USSR	8/5/1973	Mars orbiter/lander, arrived 3/12/74	Little data returned
Mars 7	USSR	8/9/1973	Mars orbiter/lander, arrived 3/9/74	Little data returned
Viking 1	U.S.	8/20/1975	Mars orbiter/lander, orbit 6/19/76–1980, lander 7/20/76–1982	Combined, the Viking orbiters and landers returned 50,000+ photos
Viking 2	U.S.	9/9/1975	Mars orbiter/lander, orbit 8/7/76–1987, lander 9/3/76–1980	Combined, the Viking orbiters and landers returned 50,000+ photos
Phobos 1	USSR	7/7/1988	Mars/Phobos orbiter/lander	Lost 8/88 en route to Mars
Phobos 2	USSR	7/12/1988	Mars/Phobos orbiter/lander	Lost 3/89 near Phobos
Mars Observer	U.S.	9/25/1992	Orbiter	Lost just before Mars arrival 8/21/93
Mars Global Surveyor	U.S.	11/7/1996	Orbiter, arrived 9/12/97	Currently conducting prime mission of science mapping
Mars 96	Russia	11/16/1996	Orbiter and landers	Launch vehicle failed
Mars Pathfinder	U.S.	12/4/1996	Mars lander and rover, landed 7/4/97	Last transmission 9/27/97
Nozomi (Planet-B)	Japan	7/4/1998	Mars orbiter, currently in orbit around the sun	Mars arrival delayed to 12/03 due to propulsion problem
Mars Climate Orbiter	U.S.	12/11/1998	Orbiter	Lost on arrival at Mars 9/23/99
Mars Polar Lander/Deep Space 2	U.S.	1/3/1999	Lander/descent probes to explore Martian south pole	Lost on arrival 12/3/99

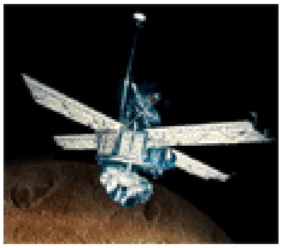
Source: <http://mars.jpl.nasa.gov/missions/log/index.html>.

Exhibit 3 Gallery of U.S. Mars Spacecraft

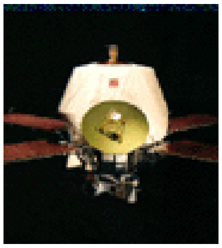
Mariner 3 & 4



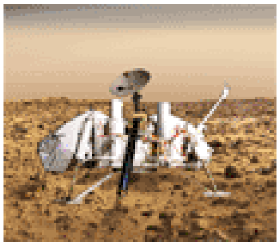
Mariner 6 & 7



Mariner 8 & 9

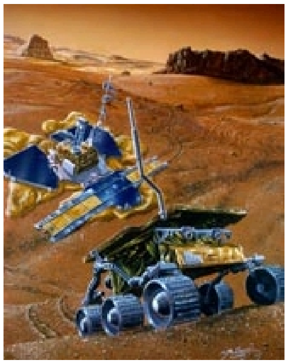


Viking 1 & 2



Mars Observer

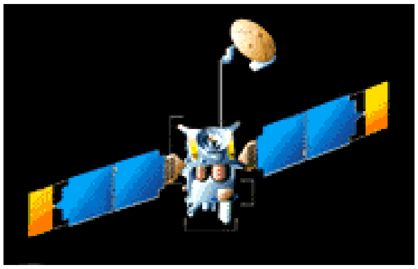
Mars Pathfinder



Mars Climate Orbiter

Mars Polar Lander

Mars Global Surveyor



Source: <http://mars.jpl.nasa.gov/gallery/spacecraft/index.html>.

Exhibit 4 Viking Photographs

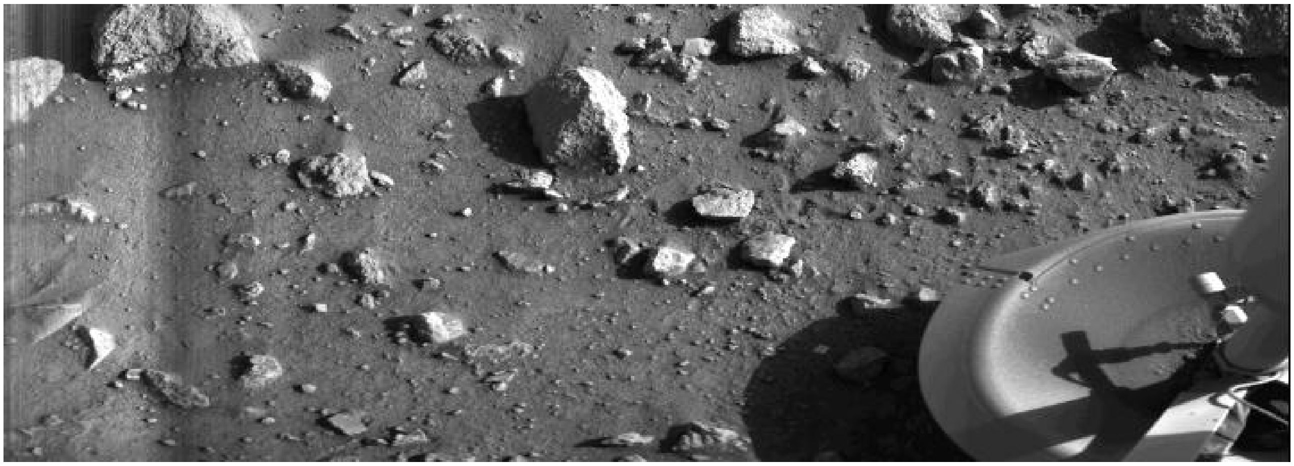


Image Title: **First Photograph Taken On Mars Surface**

This is the first photograph ever taken on the surface of the planet Mars. It was obtained by Viking 1 just minutes after the spacecraft landed successfully early today. The center of the image is about 1.4 meters (five feet) from Viking Lander camera #2. We see both rocks and finely granulated material--sand or dust. Many of the small foreground rocks are flat with angular facets. Several larger rocks exhibit irregular surfaces with pits and the large rock at top left shows intersecting linear cracks. At right is a portion of footpad #2. The shadow to the left of the footpad clearly exhibits detail, due to scattering of light either from the Martian atmosphere or from the spacecraft, observable because the Martian sky scatters light into shadowed areas.

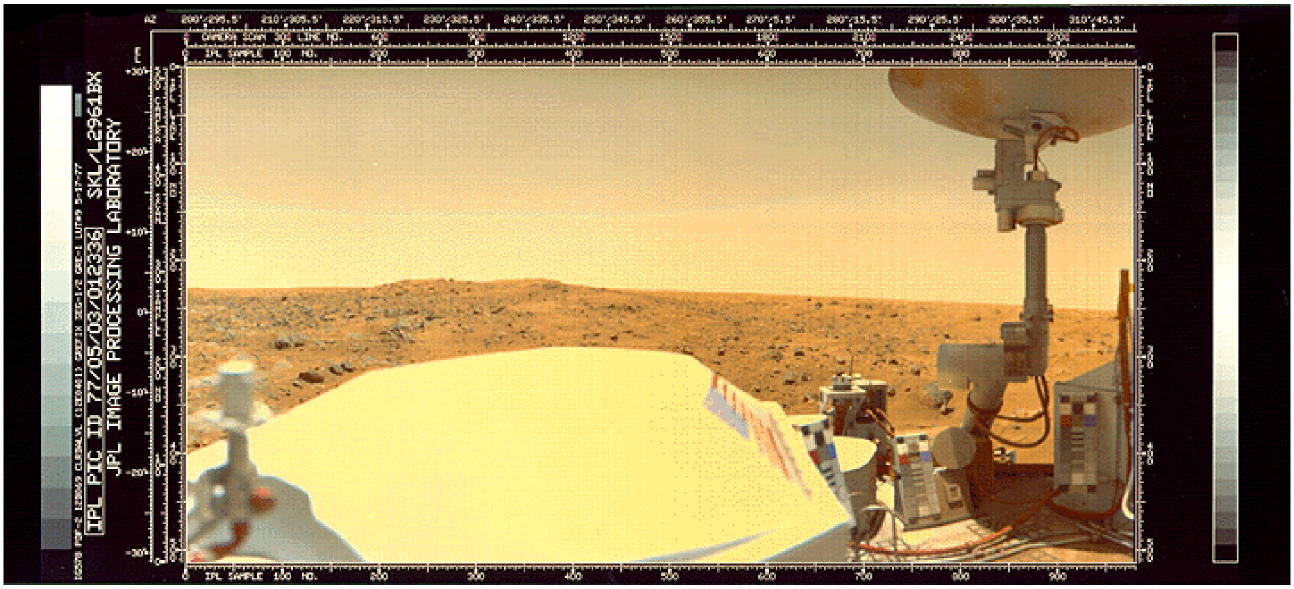


Image Title: **Color view of Chryse Planitia looking NW over the Viking 1 Lander**

Viking 1 Lander image of Chryse Planitia looking over the lander. The large white object at lower left and center, with the American flag on the side, is the radiothermal generator (RTG) cover. The high-gain S-band antenna is at upper right. The view, from 22 N, 50 W, is to the northwest. Chryse Planitia is a wide, low plain covered with large rocks and loose sand and dust. The image was taken on 30 August 1976, a little over a month after landing. (Viking 1 Lander, 12B069)

Source: <http://www.tufts.edu/as/wright_center/work_con_lec/astro_wkshp_res/astro_wkshp_cd_2001/images/viking_gallery/pages/viking_gallery.html> and <http://mars.jpl.nasa.gov/gallery/martianterrain/PIA00381.html>.

Exhibit 5 How the Mars Pathfinder Rover Came to Use Commercial Motors

Every time I'd go down to visit the mobility team I'd find them picking apart motors to figure out which one would be best on Mars. They disassembled five or six different motors before they discovered the strengths of a powerful little fishing reel-size brushed motor made by the Swiss company Maxon. They liked the fact that the motor brushes were made of precious metal, which is more hardy in space, and they liked the capacitor that dissipated excess energy in the motor. The only problem was when you took the capacitor down to minus 100 degrees, it sometimes shattered, leaving shrapnel inside the motor. With a few modifications to compensate for the flaws, Howard Eisen believed, these motors would be adequate on Mars. He called Maxon's U.S. representative to discuss these modifications. The Maxon guy told Howard he was nuts to ask for changes. Howard was asking for special work for a meager order of 100.

I realized this was not the kind of negotiation we could conduct by phone and fax. In order to convince the CEO of Maxon that it was worth his while to make expensive changes on his $100 motors, we'd need to rely on personal charm and invoke the mystery and romance of space. I was scheduled to give a talk in France about machine vision for which the conference was paying my travel. I couldn't negotiate about motors but Brian Wilcox and I could write the paper and coach Howard on machine vision. I told Howard to present my paper and, while he happened to be in the neighborhood, drop by Switzerland and pay a call on Maxon.

Howard flew into Lucerne and spent the day sightseeing. The next day he took the train to the tiny Swiss town of Sachseln where Maxon headquarters are located. He carried with him drawings of the rover and the way Pathfinder might land on Mars, as well as an X-ray of a shattered capacitor to illustrate what he wanted the company to modify as well as some of the data his team had developed on the motor. After all, Maxon was a huge motor manufacturer and twenty-five year old Howard wanted to be well prepared for his meeting with the head of the company and the chief engineer.

When Howard sat down with the U.S. sales representative and the company's lead engineer he unfurled the exhaustive report he and his team had compiled on the subtleties and performance of this little motor. The technical discussion—engineer to engineer—went smoothly. The Maxon engineer was amazed by how well Howard knew the motor. When the president of Intergalactic AG, Maxon's parent company came in, the tone of the meeting changed. The president was concerned that modifying these motors for such a small order would be too much of a drain on the company's resources. This was Howard's cue.

The day before, Howard had visited the Swiss transport museum, Verkerhaus, which is mainly full of old trains and carriages. He was naturally drawn to the exhibit on space exploration, which featured precisely one item: a latch a Swiss company had made for a weather satellite.

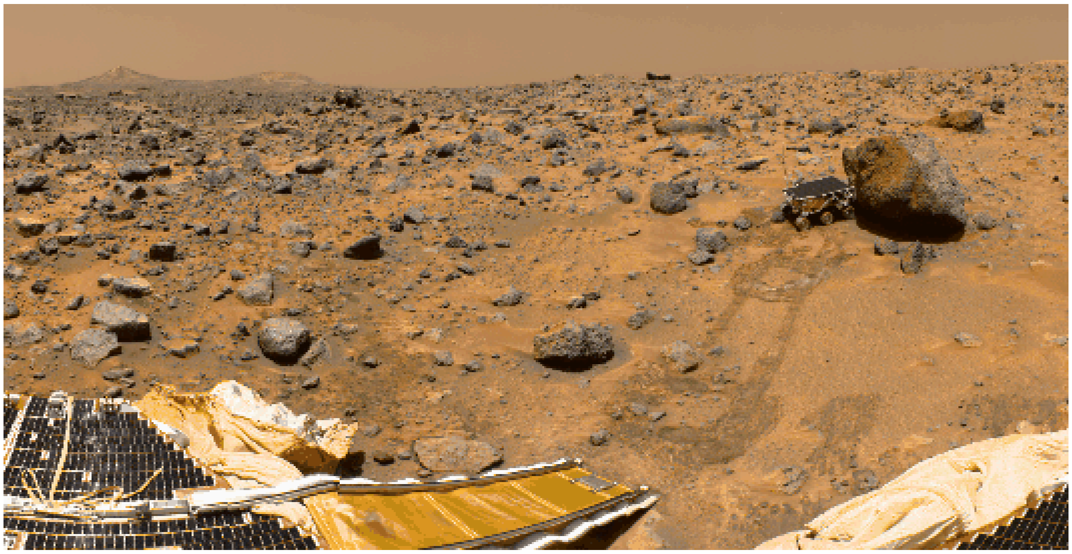
Howard switched from talking about motors to remarking on how much he'd enjoyed visiting Verkerhaus. The president responded that everyone was very proud of the museum and he was a big fan of it as well. Howard observed how small the space section of the museum was: that one tiny latch. He suggested that in three years, if the two of them could come to an agreement, Maxon could rightly augment that display with its electric motor, the one that propelled the rover around Mars.

That pretty much completed the negotiation for Howard. By the time he left Sachlesn he'd walked the factory floor with the chief engineer to establish that there was a way we could determine the history of all the motors, persuaded them to let him see the technical drawings of the motor design, convinced them to make the modifications we wanted and to send us the performance report the company generates when it tests each motor. Maxon found that there were easy ways to accomplish the modifications that increased the motor's reliability in the harsh Martian environment. In the end, Maxon increased the price of each motor by less that $10.00.

Definitely worth the money we spent to send Howard from France to Switzerland.

Source: From *Managing Martians* by Donna Shirley, copyright © 1998 by Donna Shirley. Used by permission of Broadway Books, a division of Random House, Inc.

Exhibit 6 Image from the Pathfinder/Sojourner Mission



This is a sub-section of the "geometrically improved, color enhanced" version of the 360-degree panorama heretofore known as the "Gallery Pan", the first contiguous, uniform panorama taken by the Imager for Mars Pathfinder (IMP) over the course of Sols 8, 9, and 10. Different regions were imaged at different times over the three Martian days to acquire consistent lighting and shadow conditions for all areas of the panorama.

The IMP is a stereo imaging system that, in its fully deployed configuration, stands 1.8 meters above the Martian surface, and has a resolution of two millimeters at a range of two meters. In this geometrically improved version of the panorama, distortion due to a 2.5 degree tilt in the IMP camera mast has been removed, effectively flattening the horizon. The IMP has color capability provided by 24 selectable filters—twelve filters per "eye". Its red, green, and blue filters were used to take this image. The color was digitally balanced according to the color transmittance capability of a high-resolution TV at the Jet Propulsion Laboratory (JPL), and is dependent on that device. In this color enhanced version of the panorama, detail in surface features are brought out via changes to saturation and intensity, holding the original hue constant. A threshold was applied to avoid changes to the sky.

On the horizon the double "Twin Peaks" are visible, about 1-2 kilometers away. The rock "Couch" is the dark, curved rock at right of Twin Peaks. A Lander petal is visible on the left, showing the fully deployed rear ramp, which rover Sojourner used to descend to the surface of Mars on July 5. Immediately to the left of the rear ramp is the rock "Barnacle Bill", which scientists found to be andesitic, possibly indicating that it is a volcanic rock (a true andesite) or a physical mixture of particles. Just beyond Barnacle Bill, rover tracks lead to Sojourner, shown using its Alpha Proton X-Ray Spectrometer (APXS) instrument to study the large rock "Yogi". Yogi, low in quartz content, appears to be more primitive than Barnacle Bill, and appears more like the common basalts found on Earth.

The tracks and circular pattern in the soil leading up to Yogi were part of Sojourner's soil mechanics experiments, in which varying amounts of pressure were applied to the wheels in order to determine physical properties of the soil. During its traverse to Yogi the rover stirred the soil and exposed material from several centimeters in depth. During one of the turns to deploy Sojourner's Alpha Proton X-Ray Spectrometer, the wheels dug particularly deeply and exposed white material. Spectra of this white material show it is virtually identical to the rock "Scooby Doo", and such white material may underlie much of the site. Deflated airbags are visible at the perimeter of the Lander petals.

Mars Pathfinder is the second in NASA's Discovery program of low-cost spacecraft with highly focused science goals. The Jet Propulsion Laboratory, Pasadena, CA, developed and manages the Mars Pathfinder mission for NASA's Office of Space Science, Washington, D.C. JPL is an operating division of the California Institute of Technology (Caltech). The IMP was developed by the University of Arizona Lunar and Planetary Laboratory under contract to JPL. Peter Smith is the Principal Investigator.

Source: <http://mars.jpl.nasa.gov/MPF/ops/Nov97.html>.

Exhibit 7 Selected Planetary Mission Details

Mission	Launch	Type[a]	Weight[b] (lbs)	Cost[c] ($Mn)	Cost[d] (2000$)	Outcome	Comments
"Traditional" Missions							
Mars Mariner 8 & 9	1971	O	2,196 (each)	135	*684*	Success	Two identical craft built and flown
Mars Viking 1 & 2 (Mars)	1975	O+L	7,700 (each)	875	3,700	Success	Two identical craft built and flown
Mars Observer (MO)	1992	O	2,240	479	663	Failure	Some of the instruments flew on the later MGS mission (below)
Pioneer (Venus)	1978	O	1,140	82[c]	322	Success	
Magellan (Venus)	1989	O	2,282	407	535	Success	
Galileo (Jupiter)	1989	O+P	2,856	892	1,330	Success	Orbiter dropped probe into Jovian atmosphere
Cassini (Saturn)	1997	O	5,551	1,386	*1,691*	In Flight	
"Faster, Better, Cheaper" Missions							
Mars Pathfinder	1996	L	1,256	195	220	Success	First FBC mission
Mars Global Surveyor (MGS)	1996	O	1,479	250[f]	250	Success[g]	Recovery mission—flew 6 of 8 instruments from the MO mission
Mars Climate Orbiter (MCO)	1998	O	745	80	*84*	Failure	
Mars Polar Lander (MPL)	1998	L+P	1,129	110[h]	*116*	Failure	

Source: H.E. McCurdy; Robert Godwin, *Mars: The NASA Mission Reports* (Burlington, Ontario, Canada: Apogee Books, 2000); NASA and JPL Web sites; casewriter analyses.

[a] Type: O=Orbiter, L=Lander, P=Probe.

[b] Weight excluding launch vehicle and propellants. Note that launch mass is a major indicator of a spacecraft's complexity.

[c] Development cost; excludes launch vehicle and mission support costs. Note that in missions where two craft were built, the incremental cost for the second craft was negligible compared with the overall mission cost. For example, the Viking mission originally planned for a third lander at an incremental cost of only $25mn in real dollars (source: McCurdy).

[d] Where unavailable, 2000$ figures are estimated by casewriter (in italics); NASA data used for inflation estimates, inflation rate of 2.5% assumed for missing years.

[e] Cost to build and operate for 10 years was $125mn; development costs assumed to be 66% of this total (data from Galileo through 1997).

[f] The design was primarily derived from the Mars Observer spacecraft; according to The Mars Program Independent Assessment Team summary report completed in March 2000, "The development cost plus the estimated value of the inheritance was approximately $250mn." Actual development costs were reported as being between $131 million to $155 million.

[g] A problem with aerobraking delayed the start of the spacecraft's mapping mission.

[h] The probe, named Deep Space 1, was developed in a separate project.

Exhibit 8 Faster, Better, Cheaper Mission Outcomes as of March 1999

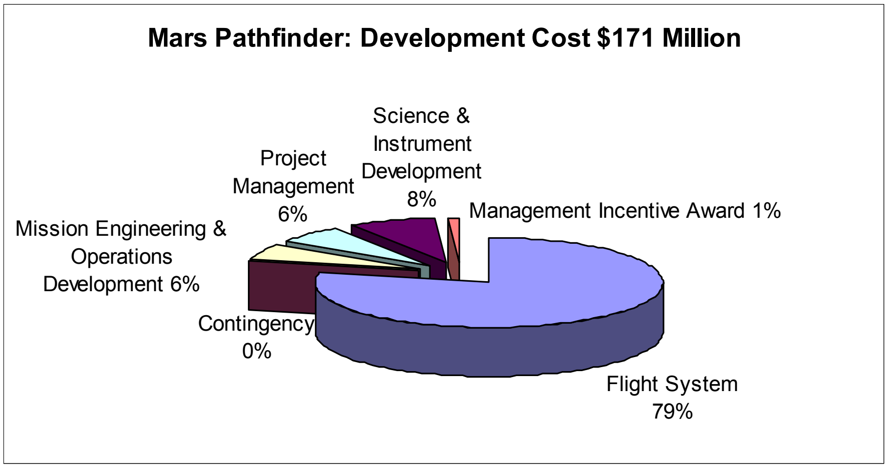
Mission	Program[a]	Launch Date	Outcome
Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPLEX)	Small Explorer (SMEX)	July 3, 1992	Success
NEAR (Near Earth Asteroid Rendezvous)	Discovery	February 17, 1996	Success
Fast Auroral Snapshot Explorer (FAST)	Small Explorer (SMEX)	August 21, 1996	Success
Mars Global Surveyor	Mars Surveyor	November 7, 1996	Success
Mars Pathfinder	Discovery	December 4, 1996	Success
Lewis	Small Satellite Technology Initiative	August 22, 1997	Failure
Lunar Prospector	Discovery	January 6, 1998	Success
Transition Region and Coronal Explorer	Small Explorer (SMEX)	April 2, 1998	Success
Deep Space 1	New Millennium	October 24, 1998	Success
Submillimeter Wave Astronomy Satellite (SWAS)	Small Explorer (SMEX)	December 4, 1998	Success
Mars Climate Orbiter	Mars Surveyor	December 11, 1998	Failure
Deep Space 2	New Millennium	January 3, 1999	Failure (part of MPL)
Mars Polar Lander (MPL)	Mars Surveyor	January 3, 1999	Failure
Stardust	Discovery	February 7, 1999	In progress
Wide-Field Infrared Explorer (WIRE)	Small Explorer (SMEX)	March 4, 1999	Failure
Clark Earth Observing Satellite	Small Satellite Technology Initiative	N/A	Terminated[b]

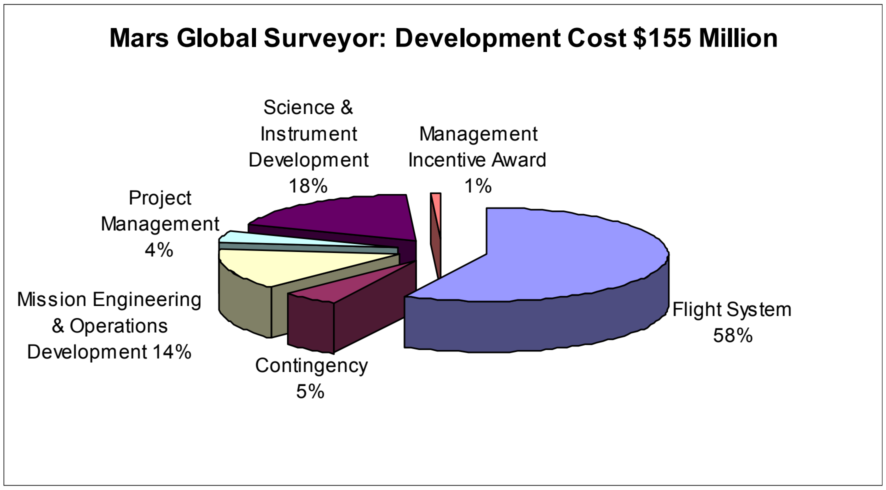
Source: McCurdy.

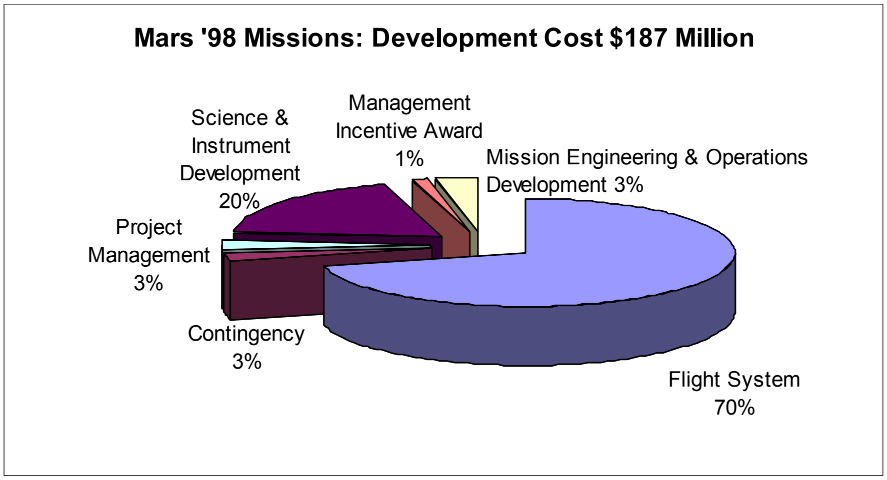
[a] Missions were part of five programs: Discovery; Mars Surveyor; New Millenium (a program to demonstrate new technologies for future missions); Small Explorer; and the Small Satellite Technology Initiative.

[b] Mission terminated due to cost and schedule overruns.

Exhibit 9 Cost Structure of Selected Mars Missions







Source: John McNamee of JPL.

Exhibit 10 NASA Budget

TOTAL (millions of real dollars)			**13,600.8**
Human Space Flight	**5,487.7**	**Science, Aeronautics & Technology**	**5,580.9**
International Space Station	2,323.1	Space Science[a]	2,192.8
Space Flight Operations (Space Shuttle)	2,979.5	Life & Microgravity Sciences & Applications	274.7
Payload Utilization & Operations	165.1	Earth Science	1,443.4
Payload & ELV Support		Aerospace Technology	1,124.9
Investments & Support		Mission Communication Services	406.3
		Space Operations	
Mission Support	**2,532.2**	Academic Programs	138.8
Safety, Mission Assurance, Engineering & Advanced Concepts	43.0	**Inspector General**	**20.0**
Space Communication Services	89.7		
Research & Program Management	2,217.6		
Construction of Facilities	181.9		

Space Science[a] (thousands of dollars)	**2,192,785**
Chandra X-Ray Observatory	4,100
Space Infrared Telescope Facility	123,433
Hubble Space Telescope (Development)	160,100
Relativity (GP-B) Mission	49,900
Thermosphere, Ionosphere, Mesosphere Energetics & Dynamics	27,500
Stratosphere Observatory For Infrared Astronomy	39,000
Payload & Instrument Development	13,600
Explorers	122,300
Discovery	154,800
Mars Surveyor	248,400
Mission Operations	75,400
Supporting Research & Technology	1,179,285
Investments	--
Construction of Facilities	--
Undistributed Reduction	-5,000

Source: <http://ifmp.nasa.gov/codeb/budget2001/HTML/fy01_myb.htm>.

[a] The Office of Space Science (OSS) at NASA HQ exercised ultimate control and responsibility for all NASA's space-science activities. Consisting of 80 people, OSS worked with the various NASA Centers, the scientific community, other U.S. government agencies, the president's Office of Management and Budget, the Congress, and NASA's international partners. OSS developed the budget for NASA, allocating funds approved by Congress to the various programs. In this task, it received guidance and advice on science priorities from the Space Science Advisory Committee, whose members included scientists from academia, industry, and government labs.