Policy and Findings

President Bush has set forth two major goals for the U.S. space program — developing a permanent human presence on the Moon, and landing a human crew on Mars — under the broad principle of extending "human presence and activity beyond Earth orbit into the solar system."[1] These are two of many goals for civilian space activities the U.S. Government could pursue.[2] The Advisory Committee on the Future of the U.S. Space Program[3] has recommended that "the 'mission-oriented' portion of the program [NASA'S] be designed to support two major undertakings: a Mission to Planet Earth and a Mission from Planet Earth.''[4] As seen by the Committee, the Mission to Planet Earth emphasizes using robotic space technology to tackle environmental and other Earth-bound problems. The Mission ***from*** Planet Earth would focus on the exploration of space, using human crews as well as robotic systems. In the Committee's view, both mission foci should rest on the foundation of space science and an enabling technology infrastructure.[5]

During this decade, Congress will be faced with a series of decisions concerning whether or not to invest public dollars to send human crews back to the Moon and/or on to Mars,[6] decisions that cannot be reduced to scientific and technological considerations alone. Experience suggests that management, politics, and budgets — as they interact with technical factors — will shape the success or failure of ***any*** initiative to explore space, whether solely with robotic devices, or using both robots and humans. **Mission from P1anet Earth will be very complex, requiring new technologies and taking many years. It will therefore be shaped by a continuous decision process extending over numerous budget cycles. The funding and political support for an initiative to explore the Moon and Mars must be provided over many Presidencies and Congresses.** Therefore, projects should be defined with an eye to returning nearterm benefits. Because the cast of participants will change over time (in 2-,4-, and 6-year intervals), funding commitments to Mission from Planet Earth will have to be renewed on the basis of performance by NASA and the other agencies, and the standards of performance will change as new information is gained.

Both humans and robotic spacecraft will contribute to solar system exploration whether or not humans set foot on the Moon or Mars within the next three decades. The Congress must decide the appropriate mix of humans and robotic technologies to fund within the set of projects that make up a Mission from Planet Earth.[7] The ***timing*** of its decisions will depend upon Congress' view of the President's proposed timetable of enabling human crews to reach the surface of Mars by 2019. **Given the imperative to reduce Federal spending, acceptance of the President's timetable might greatly circumscribe the options for using automation and robotic (A&R) technologies to**

[1] The White House, "National Space Policy," Nov. 2, 1989, p. 1.

[2] See, e.g., the list in U.S. Congress, Office of Technology Assessment, *civilian Space Stations and the U.S. Future in Space*, OTA-STI-242 (Washington, DC: U.S. Government Printing Office, November 1984), pp. 15-16.

[3] Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the US. Space Program* (Washington, DC: U.S. Government Printing Office, December 1990). The National Space Council and NASA appointed the Advisory Committee to examine the goals and managment of the U.S. space program. Norman Augustine, CEO of Martin Marietta Corp., served as its chair.

[4] Ibid, p. 5.

[5] Ibid, p. vi and 5.

[6] Although the Moon's surface would provide human crews with experience in living and working in space, the Nation could decide to proceed directly to Mars.

[7] This report entered the publishing process before the Synthesis Group report on alternative technologies and exploration architectures was released. Hence, it was unable to consider the Synthesis Group's findings.

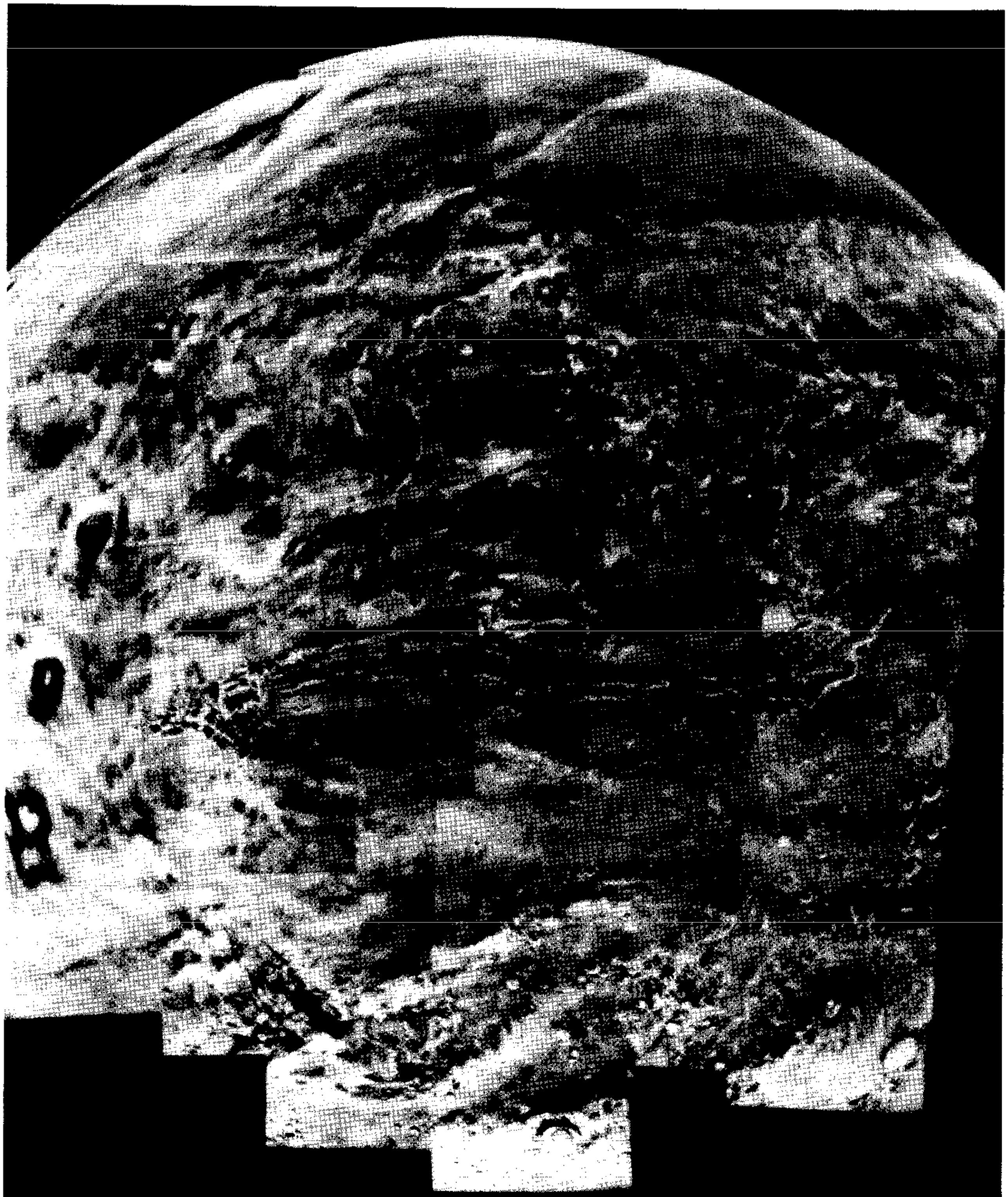

Photo credit: National Aeronautics and Space Administration

Mosaic of 102 images of Mars taken by NASA's Viking Orbiter 1, Feb. 22, 1980. Valles Marineris, which is as long as the distance from New York to San Francisco, stretches across the center. Three huge volcanoes of the Tharsis region appear on the left.

support planetary exploration, and require a major emphasis on technologies and systems to support human crews. Taking a broader view of the many possible paths for the Mission from Planet Earth permits consideration of a wider range of technological options and timetables. For example, Congress could:

1. ***Defer decisions on a Mission from Planet Earth indefinitely and fund the scientific exploration of the Moon and Mars within the existing planetary exploration program.***

   If Congress chose to defer decisions on human exploration of the Moon and Mars, it could continue to fund the scientific exploration of these two celestial bodies within the existing planetary exploration program. This approach would place the exploration of the Moon and Mars within the context of other space science priorities. However, unless Congress appropriated a higher proportion of funding for space science than the customary 20 percent of NASA's total budget,[8] or sharply reduced funding for other space science missions, this choice would allow only modest exploration efforts.

2. ***Agree in principle with the goals of a Mission from Planet Earth, but emphasize the development and use of A&R technologies to accomplish them.***

   Alternatively, if Congress supported the long-term goal of human exploration of the solar system, and felt that robotic technologies should receive greater emphasis, it could endorse the President's goals in principle but defer funding of systems to support human exploration until better information on risks and costs becomes available. It could in the meantime direct NASA to enhance its efforts in robotic exploration of the Moon and Mars. As scientists learn more about these celestial bodies, and develop more capable robotics technologies, Congress could then decide whether or not to fund the development of technologies necessary for supporting human exploration. This option would have the effect of emphasizing the scientific exploration of the Moon and Mars compared to the rest of the space science effort. It would also extend the President's proposed timetable for humans to set foot on Mars by several years and allow NASA to gather additional scientific information to support a later congressional funding decision on human exploration. This option would require additional funding for exploration over current allocations.

3. ***Agree in principle with the long-term goals of a Mission from Planet Earth, but with to focus on measured efforts to develop technologies supporting human exploration.***

   If Congress agreed with the long-term goal of human exploration of the solar system, but felt that the United States should proceed cautiously with human exploration, as well as learn much more about the conditions on Mars, the risks to human life, and the predicted total costs of a Mission from Planet Earth, it could endorse the President's goals and fund selected technologies required for human exploration, while also funding the development of robotic technologies to aid human explorers. For example, Congress could ask NASA and the Department of Defense (DoD) to proceed with the development of propulsion and other space transportation technologies for a new launch system, but defer development of in-space nuclear propulsion, or technologies to provide artificial gravity in flight until more is known about the space environmental risks humans face. In order to assist

[8] The space science and applications budget has equaled about 20 percent of NASA's total budget since the mid-1970s. Ronald M. Konkel, "Space Science in the Budget: An Analysis of Budgets and Resource Allocation the NASA, FY 1961 1989," Center for Space and Geosciences Policy, University of Colorado, Boulder, CO, May 1990.

its later decisions on funding a permanent lunar base, or human exploration of Mars, Congress could ask NASA to study key scientific and technological issues and report back to Congress at predetermined intervals.

4. ***Accept the President timetable of reaching Mars by 2019.***

Finally, Congress could accept the President's timetable of reaching Mars by 2019 and decide to fund projects designed to achieve that goal. This option would require NASA, DoD, and the Department of Energy (DOE) to begin a range of studies detailing the technical options for meeting the President's goal. It would also require the near-term development of a heavy-lift launch system, life-support systems, and other technologies necessary to transport humans to the Moon and Mars and support them on the surface. Finally, this option would also require development of A&R technologies to gather early scientific knowledge of Mars and to improve human productivity on both the Moon and Mars.

In its report, the Advisory Committee on the Future of the U.S. Space Program shares "the view of the President that the long term magnet for the manned space program is the planet Mars." However, it suggested that "a program with the ultimate, ***Zong-term*** objective of human exploration of Mars should be tailored to respond to the availability of funding, rather than to adhering to a rigid schedule."[9] Options 2 and 3 fit within the Committee's recommendations, but emphasize somewhat different approaches to technologies and schedule.

PLANETARY EXPLORATION POLICY AND NATIONAL GOALS

In recent debate, the space program's close connection to broad national concerns has manifested itself in the propositions that human exploration of the Moon and Mars would help reestablish ***U.S.*** leadership in space,[10] further the development of U.S. science and technology,[11] and assist its economic competitiveness abroad.[12] In 1986, the National Commission on Space advanced the additional view that the solar system is "humanity's extended home" and that the United States should use its economic strength to lead the rest of the world in exploring, and eventually settling, the Moon and Mars.[13] According to this view, the technological challenge of returning to the Moon and sending humans to explore Mars would create strong pub-Iic interest, nationally and internationally, and enhance attention to science and technology.[14]

These varied perspectives — destiny, world leadership, economic expansion — raise several overarching issues for Congress to consider in authorizing and funding the U.S. civilian space program of the 1990s. The roles of A&R in space exploration are embedded in each of them:

- In the 1960s, the Kennedy and Johnson administrations and Congress explicitly designed the Apollo program to establish U.S. preeminence in science and technology. Would demonstrating preeminence in the next century through planetary exploration by robots or human crews serve U.S. political and economic goals?
- Over the years, the United States has used the civilian space program to support both

[9] Advisory Committee on the Future of the U.S. Space Program, op. cit., footnote 3, p. 6.

[10] Sally K. Ride, *Leadership and America's Future in Space* (Washington, DC: National Aeronautics and Space Administration, August 1987).

[11] Arnold D. Aldrich, "Myth and Reality: NASA and the Space Exploration Initiative," paper presented at the Space Exploration 90 conference, Oct. 30, 1990.

[12] Charles Walker, "Remarks to the Scientists' Hearing on Human Mission to Mars," *Journal of the Federation of American Scientists (FAS)*, vol. 44, No. 1, January/Febuary 1991, p. 14.

[13] National Commission on Space, *Pioneering the Space Frontier: The Report of the National Commission on Space* (New York, NY: Ballantine, 1986), pp. 3-4.

[14] Synthesis Group, *America at the Threshold* (Washington, DC: The White House, June 1991), pp. 104-111.

competitive and cooperative ends. Should it view space exploration primarily as a vehicle for international competition or as an instrument for cooperation? Or can it effectively pursue both objectives?

- Would public investments in space A&R, or in technologies for supporting humans in space, contribute to overall science and technology goals, including education?

Another issue emerges from consideration of the organization and management of the Mission from Planet Earth:

- The United States has funded the civilian space program in part to enhance America's skills in science and technology. The Mission from Planet Earth would employ both people and machines in locations ranging from the surface of Earth to the surfaces of the Moon and Mars. What is the proper mix of capabilities, locations, and timing, given U.S. economic, political, scientific, and technological goals and constraints? These judgments must be made within the context of competing national priorities and should include estimates of the costs and risks.

A detailed examination and resolution of these issues is beyond the scope of this report. The following discussion outlines the considerations that policymakers face in reaching decisions on them.

From its inception, the U.S. civilian space program has been an instrument of U.S. domestic and foreign policy;[15] its structure and early direction resulted directly from the tensions of the cold war.[16] Because most spending on space activities still flows from the public purse,[17] overall domestic and foreign policy will continue to dominate decisions regarding these activities.[18]

In 1%1 when President Kennedy urged Congress to support the Apollo program the United States was in midst of the cold war. Policymakers then felt that it was particularly important to demonstrate U.S. technological competence in an arena in which our chief political and military competitor had taken the lead. The United States and the Soviet Union were clearly in a space race.[19] The U.S. economy was strong and growing, and the Federal Government experienced modest budget surpluses.

Today, the political, military, and economic character of the world is radically different than it was even on July 20, 1989, when President Bush outlined his plan for human exploration of the solar system. Relations between the Soviet Union and the United States have moved from implacable opposition to guarded cooperation. The Soviet Union is experiencing considerable internal political and economic stress, the Warsaw Pact has dissolved, and central Eastern Europe is undergoing radical and trying political and economic change. U.S. and NATO policies are increasingly tending toward cooperation with the Soviet Union, to help it move toward democracy and a modem economy, and deemphasizing political competition.[20] During the recent crisis in the Persian Gulf, e.g., the United States sought cooperation with the Soviet Union, as well as with our traditional allies.

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[15] Walter McDougall, *The Heavens and the Earth* (New York, NY: Basic Books, Inc., 1985).

[16] Vernon Van Dyke, *Pride and Power: The Rationale of the Space program* (Urbana, IL: University of Illinois Press, 1964); John M. Logsdon, *The Decision To Go to the Moon* (Boston, MA: MIT Press, 1970).

[17] A small portion of total civilian expenditures on space derive from private investment. Most of these depend on Government contracts: Henry Hertzfeld, "Trends in International Space Activity." In *The U.S. Aerospace Industry in the 1990's: A Global Perspective,* Research Center, Aerospace Industries Association of America, forthcoming, September 1991.

[18] The Bush Administrations 1989 statement of space policy refers explicitly to broader objectives in stating that the objectives of the space program "require United States preeminence in the key areas of space activity critical to achieving our national security, scientific, technical, economic, and foreign policy goals."

[19] The February 1991 NOVA special documentary series on the Soviet space program reveals that Soviet officials also saw themselves in a race with the United States for supremacy in space.

[20] Manfred Worner, "The Atlantic Alliance in the New Era," *NATO Review,* vol. 39, No. 1, pp. 3-10.

Unlike 30 years ago, our allies are now our strong economic competitors, particularly in defense and other high technology industries.[21] **How the U.S. Government chooses to invest in R&D will have profound implications for economic competition. Although demonstrating U.S. technological prowess with a major space initiative involving human spaceflight would probably strengthen U.S. leadership in space, it is not clear what message that feat would send to the rest of the world.** Neither the Europeans nor the Japanese have placed the same emphasis on putting humans into space as have the United States and the Soviet Union. The European Space Agency has expressed an interest in exploring Mars robotically,[22] and the Japanese have announced plans to send robotic craft to the Moon.[23] The Soviet Union has reduced its funding for supporting a human presence in space,[24] and, given its current fiscal and political problems, it appears to lack the financial and technological resources to mount a human mission to Mars on its own. Hence, **for the next decade or two, the United States has no effective competitors in sending human missions to the Moon or Mars. Therefore, although a U.S. initiative to send human explorers to the Moon or Mars would be an accomplishment, it would not be a race with other nations. Would the United States be better or worse off than nations that spent R&D funds to realize more prosaic goals?**

Although Japan and the countries of Europe combined spend much less on space activities than the United States (table 2-l), Japanese and European technological capabilities in space and in larger areas of the economy have grown substantially over the last two decades. Europe's relative emphasis on space science, space applications,[25] and space transportation has enabled it to pose a formidable competitive challenge to U.S. space industries.[26] Both the Japanese and the Europeans have generally sought autonomy in these areas, using cooperative ventures with the United States to help achieve it. Japan and the European countries tend to enter into technology development that they perceive relates directly to their economies over the near and long term. The space A&R programs of Canada, Japan, and Europe, e.g., are relatively well integrated in content; represent a common thrust within industry, academia, and government; and focus on goals of interest to the nation's economy and competitive-

Table 2-1 -Spending on Civilian Space Activities by the World's Major Industrialized Nations

Country	Space budget (fiscal year)
Canada	$285 million (4/90-3/91)
European Space Agency (ESA)	$2.2 billion (1/90-12/90)
France	$1.7 billion (1/90-12/90) [$601 million to ESA]
Germany	$911 million (1/90-12/90) [$507 million to ESA]
Italy	$976 million (1/90-12/90) [$375 miiiion to ESA]
Japan	$1.2 billion (4/90-3/91)
United Kingdom	$296 million (4/89-3/90) [$134.6 million to ESA]
Soviet Union	$4.8 billion (FY 1990)[a]
United States	$12.5 billion (FY 1990)

a This official estimate is likely to be much lower than actual expenditures, when compared to U.S. dollars.

SOURCE: George D. Ojalehto and Richard R. Vondrak, "A Look atthe Growing Civil Space Club," *Aeronautics and Astronautics,* February 1991, pp. 12-16,

21U.S. Congress, Office of Technology Assessment, *Arming Our Allies: Cooperation and Competition in Defense Technology,* OTA-ISC-449 (Washington, DC: U.S. Government Printing Office, May 1990).

22European Space Agency, *Mission to Mars: Report of the Mars Exploration Study Team* (Pans, France: European Space Agency, January 1990).

23T. Iwata, "NASA's Unmanned LUNAR Exploration," IAF 90-438, presented at the International Astronautical Federation Annual Meeting, Dresden, Germany, October 1990.

24Nicholas L. Johnson, *The* Soviet Year in *Space 1990* (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), pp. 98-122.

25That is, communications, meteorological observations, and land and ocean remote sensing.

26U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in U.S. Civilian Space Activities,* OTA-ISC-239 (Washington, DC: U.S. Government Printing Office, July 1985).

ness.[27] Because of their relative emphasis on achieving autonomy especially in commercially viable areas of the space enterprise, and their interest in using the space program to foster long-term economic growth, neither Japan nor the countries of Europe are likely to attempt competing with the United States in activities involving human crews in space for a decade or more.[28]

As a recent study by the Congressional Budget Office has noted, NASA's attempts to increase private investment in space activities based on NASA's efforts to support humans in space have produced limited results[29] in part because, compared to satellite communications or space remote sensing,[30] the technologies involved have relatively few direct applications to U.S. industry. Hence, although a large publicly supported program to establish a lunar base or send humans to Mars would probably create new jobs in the aerospace industry, unless carefully structured, it might not contribute significantly to U.S. economic competitiveness. If it diverted scarce resources (funding and people) away from projects having a closer connection to the U.S. economy, a major initiative involving human crews might actually undercut the U.S. international position in commercially competitive technologies.

If the experience of the Apollo program provides an appropriate guide to the future, sending human crews to explore Mars would likely create public interest in the space program and encourage some young people to enter careers in engineering, mathematics, or science. It might provide jobs for scientists and engineers faced with layoffs in the declining defense industry. However, the experience with Apollo also demonstrated that the public's primary interest was with the novelty and challenge of human spaceflight and a desire to beat the Soviet Union to the Moon. Soon after the first Apollo landing, interest waned as concern about social equity and the Vietnam War increased. Funding for the space program peaked in 1%5 and reached a low point in 1974. Although some percentage of the public maintains deep interest in human spaceflight, the government cannot take for granted continuing public support for large expenditures on the space program in competition with other pressing societal needs, in the absence of clear evidence that they would directly benefit society.[31]

THE "MIX" OF HUMAN CREWS AND ROBOTICS FOR EXPLORATION

Exploration of the solar system will require a complex mix of humans and robotic systems — as some have put it, "a partnership between humans and machines."[32] *The placement* of robotic devices and humans at different stages of the exploration process would depend on available funding and the relative advantages of humans and machines for the projected task at hand. For example, current plans call for the use of robots on Mars to carry out initial reconnaissance of the Martian surface. Among other things, robots

[27] NASA Advanced Technology Advisory Committee, 'Advancing Automation and Robotics Technolgy for the Space Station Freedom and for the U.S. Economy," Technical Memorandum 103851 (Washington, DC: Ames Research Center, National Aeronautics and Space Administration, May 1991).

[28] For budgetary reasons, Europe is now reassessing its spending for the Columbus Program to build a crew-tended free flyer, and has slowed its development of the Hermes piloted space plane.

[29] Congressional Budget Office, *Encouraging Private* Investment in *Space Activities* (Washington, DC: U.S. Government Printing Office, February 1991).

[30] The attempts to commercialize space remote sensing in the United States have met with considerable frustration. Yet a small, and growing commercial market exists, particularly in providing value-added services. See U.S. Congress, Office of Technology Assessment, *Remote Sensing and the Private Sector,* OTA-TM-ISC-20 (Washington, DC: U.S. Government Printing Office, 1984).

[31] "Twenty Yearn after America first put men on the moon, the public shows only a limited commitment to the U.S. space program. This lukewarm attitude about future space exploration is a consequence of increased awareness of domestic problems, coupled with decreased concern for the U.S.-Soviet rivalry that propelled the space race during the 1960s." George Gallup, Jr., *The Gallup Public Opinion 1989,1990,* p. 172.

[32] Louis J. Lanzerotti and Marc S. Allen, "Space Science Payoffs in an Era of Human-Machine Partnership, paper presented at the American Association for the Advancement of Science, Annual Meeting, Washington, DC, February 1991.

would explore and define the local environment and clarify the risk for humans. The human role in the partnership would be to oversee the robot's operation on the surface. Later, humans might visit the surface of Mars to explore it firsthand, using A&R technologies to support their efforts.

Nearly all the advocates of space exploration that OTA interviewed for this assessment expressed the view that humans would one day return to the Moon and set foot on the surface of Mars. They differed widely in their predictions about why and when those events would take place. Opinions regarding the most appropriate schedule differed even more widely. Some ardently support the establishment of a lunar outpost and/or the human exploration of Mars as soon as possible (by 2019 or sooner); others expressed the view that the United States should approach such projects with caution and suggested that a later date for a Mars landing would be more prudent. All supported continued robotic exploration.[33] Several opined that from a scientific standpoint, advances in A&R technologies might make the goal of landing humans on the surface of Mars superfluous, but noted that other objectives could still draw the United States to support a human expedition to the planet.

Most scientific objectives for the exploration of the Moon and Mars can be met with A&R technologies. On the Moon, robots controlled from Earth can be used to explore for lunar resources, to conduct scientific observations, and to carry out a variety of construction tasks. However, experts in field research methods believe that even with advances in automation and research, human explorers are likely to be most effective in carrying out geological field studies on the Moon and Mars, or searching for signs of indigenous existing or fossil life on Mars. These tasks involve complex skills, including recognition of subtle clues, and detailed assessment and analysis.

Both humans and machines would be involved in any program aimed at returning to the Moon or exploring Mars. For a given set of scientific objectives, the appropriate mix of duties and locations is a technical decision that should be determined by the relative advantages of each. A&R technologies provide powerful tools for studying the planets either at a distance or on the surface. Except for human reconnaissance on the lunar surface in the Apollo program, all other scientific studies of the planets and their associated moons and other satellites have been carried out with marked success using automated and robotic systems.[34] A&R experts forecast that continuing developments in using artificial intelligence and advanced control and manipulation would give A&R systems the capability to carry out advanced surface studies of the Moon and Mars, guided by humans either in situ, in nearby orbit, or on Earth. Advanced sensors, similar in many respects to those being developed for the Mission to Planet Earth, would make detailed multispectral observations from orbit much more effective than previously possible.[35]

Field geologists[36] and biologists[37] contend that imparting their skills, knowledge, and experience of fieldwork to robotic systems, acting alone, may never be possible. Although A&R experts forecast significant improvements in A&R over the next three decades, A&R devices are likely to fall short in areas in which humans excel — those that require a broad experiential database and the

[33]See also Advisory Committee on the Future of the U.S. Space Program, op. cit. footnote 3, p. 6: "such an endeavor must be preceded by further unmanned visits..."

[34]Space exploration, whether by humans or robotic devices, also carries a high degree of technical risk. As the Soviet experience with 'heir *Phobos* spacecraft reminds us, robotic devices sometimes fail, causing loss of mission or reduced effectiveness.

[35]Recent observations of the Moon by the imaging system on the Galileo Jupiter space probe illustrates how such observations can advance scientific knowledge of the planets.

[36]Paul D. Spudis and G. Jeffery Taylor, "The Roles of Humans and Robots as Field Geologists on the Moon," in *Proceedings of the 2nd Lunar Base Symposium* (San Diego, CA: Univelt, 1990).

[37]Christopher P. McKay and Carol R. Stoker, "The Early Environment and Its Evolution on Mars: Implications for Life," *Reviews of Geophysics, vol.* 27, No. 2, 1989, pp. 189-214.

Photo credit: National Aeronautics and Space Administration

An experimental planetary rover undergoing tests in a dry river bed. Nicknamed "Robby," this rover was developed by Jet Propulsion Laboratory, under contract to NASA. Robby is a six-wheel, three-body articulated vehicle that offers superior mobility compared to four-wheel, single-body vehicles. Robby has an arm to grasp soil and rock samples. Stereo cameras mounted atop the middle body allow Robby to construct a map of its local environment and navigate autonomously around obstacles to reach a predetermined goal.

ability to link disparate, unexpected observations in the field. Reconnaissance on the Moon by Apollo astronauts, e.g., provided the basis for interpreting data acquired remotely. Field scientists point out that as A&R technologies grow more sophisticated, their ability to assist fieldwork will make human explorers, whether located on-site or at great distances, much more capable than they are today. Hence, according to their view, humans, using advanced A&R technologies for support and field analysis, are likely to advance our scientific knowledge of the Moon and Mars significantly. By observing geological formations in the field, trained field geologists could provide important data on the formation and evolution of the Moon and Mars. Biologists and geologists trained in the specialized methods of exobiology would be able to search for signs of past or present life on the Martian surface.[38]

However, scientists would need to remain on the Martian surface long enough to accomplish worthwhile research and other tasks. They would also have to be relatively safe and reasonably comfortable. Soviet experience on ***Mir*** suggests that human productivity in space might be relatively low.[39] U.S. experience on the Apollo flights and on Skylab indicates the potential for higher productivity, especially if assisted by modern A&R technologies, designed to reduce the burden of routine tasks.

MANAGEMENT OF EXPLORATION

U.S. experience with large science and technology projects and long-range goals suggest that program planners need to maintain considerable planning flexibility and abroad set of intermediate goals within the general direction. Operational success in each successive phase should be favored over forcing a fit to a long-term plan.

Lessons based on experience with the space shuttle[40] and with space station ***Freedom***[41] imply that "success-oriented" planning, which leaves little room for the vagaries of the political process or technical setbacks, may lead to much higher than expected costs, and long delays in accomplishing major technical goals. A successful strategy for exploring the Moon and utilizing its re-

[38] Experience with using robotic devices to explore Lake Hoare, Antarctica, demonstrates that they provide extremely important support services. That experience suggests that planetary scientists might wish to make extensive use of A&R techniques to extend human perception into a hostile environment before attempting human presence. Learning as much as possible about the hostile environment enables the safest and most efficient use of human resources in conducting scientific research. Steven Squyres, Cornell University, personal communication, 1991.

[39] Cosmonaut Gregory Grechko, personal communication, March 1991.

[40] John M. Logsdon, "The Space Shuttle Program: A Policy Failure?" Science, vol. 232, May 30, 1986, pp. 1099-1105.

[41] Ronald D. Brunner and Radford Byerly, Jr., "The Space Station Programmed," *Space Policy*, vol. 6, No. 2, May 1990, pp. 131-145; Thomas J. Lwein and V.K. Narayanan, *Keeping the Dream Alive: Managing the Space Station Program, 1982-1986*, NASA Contractor Report 4272, National Aeronautics and Space Administration, July 1990; Howard E. McCurdy, *The Space Station Decision: Incremental Politics and Technical Choice* (Baltimore, MD: Johns Hopkins University Press, 1990).

sources and exploring Mars would include allowance for the unexpected. These lessons suggest that these goals could be met most effectively by developing an integrated strategy that includes both large and small projects, each of which contributes to the larger goal. They also suggest that a successful evolutionary strategy would include the following characteristics:

- Flexibility — Planners should not attempt to "freeze" or "lock-in" a large-scale, long-term plan tightly coupled to expected funding. A balanced, flexible plan would allow investigators to learn from experience, and give them room for changes in scope and project direction depending on information received and funding available. However, because a very flexible plan could also lead to stretchouts, reorganizations, and loss of project momentum, the areas of project flexibility need to be carefully structured.

- ***A set of intermediate, phased goals structured around a common theme —*** Planners should resist the tendency to design a large-scale project in order to include every objective under the aegis of a large program. Instead they should disaggregate the often incompatible goals of multiple constituencies, approaching the goals through multiple projects, executed either in parallel or in series. These steps would allow planners to learn from the successes or failures of early projects and factor these lessons into subsequent projects.

- ***A management structure that favors operational experience over planning —*** Experience and a judgment about what works best should be the primary test of the succeeding stages in the exploratory process, rather than a plan developed prior to the results of the first stage.

- ***Streamlined management and procurement*** – Wherever possible, contract for specified capabilities rather than specified hardware. In other words, allow industry to determine the technologies and approaches to providing the required capabilities rather than having government laboratories decide.

The scientific success of exploratory missions to the Moon and Mars will depend closely on the quality of the scientific advice NASA receives, funding stability for a long-term program, and the relative influence of scientists in designing the missions. If the Nation wishes to maximize the quality of its scientific returns,[42] scientists should have a major role in the process of deciding how exploration resources are spent. The Space Science Board of the National Academy of Sciences and other advisory groups could play a useful part in the decision process.

A number of scientists interviewed by OTA expressed serious concern that scientific objectives would soon be lost in the drive to gather only the data necessary to support a human exploratory mission to Mars. Several cited the case of the ***Ranger and Surveyor series*** of lunar probes, which prior to the Apollo program had been planned for studying the Moon. The ***Ranger*** probes were designed to photograph the lunar surface in detail. ***Surveyor*** spacecraft were to make soft landings and gather information about the chemical and physical makeup of lunar soil. The advent of the Apollo program in 1%1, "forced ***Ranger*** and ***Surveyor*** into supporting roles for the manned spaceflight program, to the intense chagrin of the space scientists."[43] Reorientation of the roles of these spacecraft forced the scientists, if they wished to continue working on lunar science, to pursue scientific questions that were possible within the constraints of the Apollo program rather than pursuing questions of highest scientific interest.[44] The two objectives may coincide, but only accidentally. Hence, the non-scientific objectives

[42]The Advisory Committee on the Future of the U.S. Space Program noted that science activity is "the fulcrum of the entire civil space effort." Advisory Committee on the Future of the U.S. Space Program, op. cit., footnote 3, p. 5.

[43]William David Compton, *Where No Man Has Gone Before* @/Washington, DC: U.S. Government Printing Office, 1989), p. 15.

[44]Ibid., chs. 2 and 3.

of the Mission from Planet Earth should not dominate the scientific objectives.

RETURNING TO THE MOON

Despite U.S. and Soviet efforts during the 1960s and early 1970s to study the Moon, scientists still have a rudimentary understanding of its structure and evolution. A detailed robotic study of the Moon would assist in understanding the geological and climatological history of the Earth.

Only about 40 percent of the lunar surface has been mapped in high resolution. Scientists have studied very little of the surface with multispectral instruments, which would provide detailed insights into the structure and composition of the Moon. Scientific exploration of the Moon could assist in resolving questions related to:[45]

- ***Formation of the Earth-Moon system*** — Did the Moon form from the impact of a giant body with Earth or directly from accretion out of the primordial material?
- ***Thermal and magmatic evolution of the Moon*** — What is the Moon's internal structure and thermal evolution?
- ***Bombardment history of the Earth-Moon system*** – What can the composition and other properties of the lunar craters tell us about the bombardment history of Earth, the evolution of Earth's climate, and the evolution of life?
- ***Nature of impact processes*** — How do craters form and evolve?
- ***Regolith formation and evolution of the Sun*** – What can studies of the regolith, the blanket of broken rock and soil that covers the Moon, tell us about the evolution of the Sun? How can regolith be used for building lunar structures?
- ***Nature of the lunar atmosphere*** – What is the nature of the extremely tenuous lunar atmosphere?

Detailed answers to these questions would require intensive lunar survey and additional samples from the Moon.

The **Moon possesses several advantages as a site for astronomical observatories operating at all wavelengths. However, the costs of lunar observatories would have to be balanced against the costs of placing observatories in competing locations, e.g., geostationary orbit. The** environmental advantages of making astronomical observations from the Moon have interested many astronomers in analyzing the scientific benefits of such sites.[46] The Moon provides a nearly atmosphere-free environment; a large, solid platform; a cold, dark sky; and the absence of wind. Specialized telescopes operating in a wide variety of wavelengths could possibly be placed on the lunar surface robotically and operated from Earth.[47] If the United States decides to establish a permanent lunar base, human crews could construct and maintain larger observatories. The lunar far side offers attractive sites for making sensitive radio observations free from radio interference emanating from Earth stations.

The lunar surface also poses several environmental challenges—among which are the constant bombardment of cosmic rays and micrometeoroids, and the effects of clinging lunar dust. The costs of building and operating lunar observatories have not been well studied in comparison to other possible sites, e.g., geostationary orbit or on Earth.[48] As astronomers continue to examine the option of placing observatories on the Moon,

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[45] Lunar Exploration Science Working Group, *A Planetary Science Strategy for the Moon,* draft, Sept. 28, 1990.

[46] The Astronomy and Astrophysics Survey Committee of the National Research Council recently recommended that "an appropriate fraction of the funding for a lunar initiative be devoted to fundamental scientific projects, which can have a wide appeal to the U.S. public; to support of scientific missions as they progress from small ground-based instruments, to modest orbital experiments; and finally, to the placement of facilities on the Moon." *The Decade of Discovery in Astronomy and Astrophysics* (Washington, DC: National Academy Press, 1991), p. 7.

[47] Russell M. Genet, "Small Robotic Telescopes on the Moon," a workshop summary, Tucson, AZ, Nov. 4-5, 1990.

[48] New technologies may vastly extend the observational capabilities of Earth-based observatories for optical wavelengths.

they should also calculate the costs (for equivalent capability) relative to other options.

A lunar base could assist human crews in studying and responding to the risks of long-term space exploration. Human crews engaged in long-term exposure to the space environment face a variety of physiological and psychological risks to their health. In order to provide adequate margins of safety for human crews, scientists must learn how to avoid cosmic rays and excessive radiation from solar flares and to offset the physiological effects of weightlessness, and extraterrestrial fractional gravity.[49] Human crews also face psychological risks from extended confinement in small quarters in an extremely hostile exterior environment. Extended stays on the lunar surface could provide scientists and crews with useful information on many of these effects, leading to reduced risks for human crews in the exploration of Mars.[50]

Exploration of the Moon using a robotic roving vehicle and other robotic devices would provide additional scientific and engineering data and give mission planners extra confidence in designing similar devices for use on Mars. They might find it fruitful to establish a robotics lunar base. Although lunar gravity is one-half that of Mars, and the lunar surface has different properties, testing robotic devices on the Moon would not only provide scientists with data of considerable scientific interest but also help reduce the risk of failure for similar devices on the surface of Mars.

Because the Moon is much closer than Mars it is possible to operate robotic devices in near real time. Communications time delays are only about 3 seconds compared to delays of 6 to 40 ***minutes*** between Earth and Mars. Tests would also allow engineers to try out alternative methods for including varying degrees of autonomy in robotic systems while exploring the Moon.[51] Because transportation and other costs are much lower than for reaching Mars, the lunar surface would provide tests of competing robotic designs. For example, recent cost estimates suggest that small rovers could be tested on the lunar surface relatively cheaply and also provide useful scientific knowledge about the Moon.[52]

Minerals and other materials extracted from the lunar surface could provide most of the material needed for a lunar base. They could also be used for building infrastructure near the Moon. If the United States were to establish a permanently inhabited lunar base, it could construct the base from the regolith. Future activities might include mining minerals for use on the Moon or in near-lunar space, or using the Moon as an energy source.[53]

EXPLORING MARS

Scientists do not sufficiently understand the Mars environment and the risks to human life to ensure relatively safe human exploration of the planet. Hence, it is too early to plan a detailed, integrated, long-term program that presupposes human exploration of Mars. However, it is not too early to begin planning a sequence of projects that would: 1) make a detailed scientific investigation of Mars, and 2) study human physiology in space to reduce the uncertainties facing human exploration.

The uncertainties facing human exploration of Mars are currently extremely large. The Mars Observer spacecraft, which NASA plans to launch in 1992 and place in Mars polar orbit in late 1993, will provide important new data that would affect planning for further exploration,

[49] Victoria Garshnek, "Exploration of Mars: The Human Aspect," *Journal of the British Interplanetary Society,* vol. 43, 1990, pp. 475-488.

[50] Initial information on psychological risks could be obtained from relatively inexpensive experiments on Earth in inhospitable geographical regions.

[51] Many of these tests could also be done on Earth. Antarctica and many desert environments provide excellent testbeds.

[52] David Scott, Scott Science and Technology, personal communication 1991.

[53] J.F. Santarius and G. L. Kulcinski, "Astrofuel: An Energy Source for the 21st Century," *Wisconsin Professional Engineer,* September/October 1989, pp. 14-18.

whether it be robotic or crew-carrying missions. Additional robotic missions that returned rock samples and surveyed more local aspects of Mars would allow mission planners to determine appropriate decision points for undertaking human missions, thereby increasing the probability of mission success.

Scientists who specialize in the reaction of humans to the space environment also lack basic knowledge of the human reaction to long-term exposure to low and near-zero gravity,[54] as well as the long-term effects of radiation from cosmic rays and solar flares.[55] Information gained by life sciences experiments on space station ***Freedom*** and ***Mir,*** or on the lunar surface, could reduce those uncertainties.

Robotics missions will be needed to explore Mars, whether or not the United States decides to land humans on Mars by 2019.

Photo credit: California Institute of Technology Jet Propulsion Laboratory

Artist's conception of a rover exploring Mars. Overhead, an orbiting satellite relays information from the rover to Earth.

All previous Mars exploration has been carried out by robotic missions. Robotic spacecraft and Mars landers will improve our ability to assess the utility of sending human explorers to Mars, compared to continued exploration by teleoperated means. If the United States decides to send humans to Mars either before or after 2019, robotic missions would be needed to:

1. advance our knowledge of the structure and evolution of Mars by studying its geology, weather, climate, and other physical and chemical characteristics — scientists also need to improve their knowledge of Mars in order to determine what role humans should play when they reach the planet;
2. reduce the risks and costs of human exploration by improving our knowledge of the planet;
3. resolve issues of soil toxicity;
4. resolve issues of possible contamination of Mars by Earth organisms and Earth by any organisms from Mars;
5. refine the planning and design of human missions – how long people should stay on the surface and what tools and robotic support they might need; and
6. identify and characterize a selection of potential landing sites.

If the United States decides to send human crews to Mars, A&R technologies are likely to provide valuable assistance to those crews while on the Martian surface. A&R technologies could provide:

1. support for field studies;
2. detailed survey before, during, and after human travel;
3. emergency support;
4. surveys of particularly difficult or dangerous regions; and
5. routine data collection.

[54] Some experts urge the development of nuclear-powered vehicles to reduce the amount of time spent in traveling to and from Mars.

[55] Victoria Garshnek, "Crucial Factor: Human-Safely Extending the Human Presence in Space," *Space Policy*, August 1989, pp. 201-216.

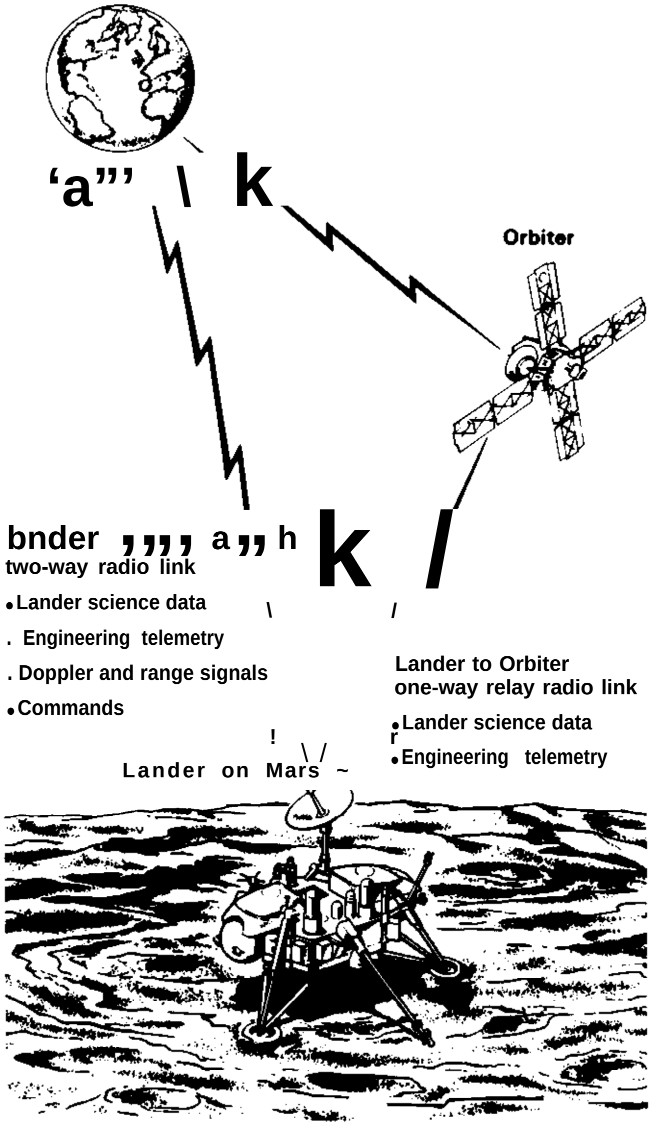

Photo credit: National Aeronautics and Space Administration

The Viking orbiting spacecraft and lander, illustrating the use of robotics technology on Mars. Viking 1 and 2 spacecraft reached Mars orbit in 1975. Each sent a lander to the surface to analyze the soil and report conditions at two locations. The orbiter served to relay information back to Earth.

Although additional information regarding surface conditions on Mars and the tolerance of human systems to microgravity, low gravity and cosmic radiation would reduce the risks to human life, a round trip to Mars would still carry considerable risk

Explorers traveling to and from Mars would suffer much higher risk than in returning to the Moon, but would experience greater challenge and adventure. A successful exploratory journey would require the functioning of many different space systems. The United States has relatively little experience in operating and maintaining human habitats in space for long periods. The Soviet Union, in contrast, has supported human crews in low-Earth orbit for periods as long as a year.[56] The United States gained valuable experience in operating the Apollo spacecraft in lunar orbit and on the Moon, at distances of 250,000 miles from Earth. U.S. scientists also gathered information concerning the effects of the space environment on humans during three stays in Skylab in 1973 and 1974, the longest of which lasted 84 days.[57]

However, depending on its relative position with respect to Earth, the distance to Mars varies from 35 to 240 million miles. Round-trip communications delays vary between about 6 to 40 minutes. Depending on the propulsion technology,[58] fuel consumption, and trajectory, a round trip to Mars could take from 1 to 3 years, including stay time on the planet. Neither the United States nor the Soviet Union has supported crew-carrying missions for such long distances and length of time in space. Reducing the risk of an exploratory journey to an acceptable level will require much more data about the planet and human physiology than we now possess, and greater experience

[56] A.D. Egorov, A.I. Grigoriev, and V.V. Bogomolov, "Medical Support on Mir," *Space*, vol. 7, No. 2, April/May 1991, pp. 27-29.

[57] W. David Compton and Charles D. Benson, *Living and Working in Space: the History of Skylab*, NASA SP-4208 (Washington, DC: National Aeronautics and Space Administration, 1983).

[58] Chemical propulsion, the only propulsion technology currently available, would require about a year to propel an interplanetary vehicle to Mars. Engineers are exploring the use of nuclear propulsion in order to reduce this time markedly. Synthesis Group, America *at the Threshold* (Washington, DC: The White House, June 1991).

living and working in space.[59] The United States and the Soviet Union could both benefit from cooperating on life sciences R&D on risk-reducing technologies.

Public reaction to the 1986 loss of ***Challenger*** demonstrated that there are important qualitative differences between public attitudes toward launching people and launching machines into space. Although human spaceflight helps create interest in space activities, the loss of life in space causes considerable public anguish. If the United States decides to send a human crew to Mars, it will at the same time have to accept the potential for loss of life, either from human error or mechanical failure and increased costs to recover from that loss.[60]

A&R RESEARCH AND DEVELOPMENT

The United States has many promising A&R technologies for use in exploring the Moon and Mars, but to date it has not sufficiently exploited them. At present NASA lacks the robotics capability to carry out a vigorous exploration program using advanced robotics.

Although the sophistication of existing technology is sufficient to carry out moderately sophisticated reconnaissance missions, in many respects, robotic technology is still in its infancy. Hence, using today's projection of future A&R capabilities for space projects two or three decades in the future might aim too low or expect too much.

For example, existing robots show great limitations in their ability to perform mechanically dexterous and flexible tasks. Yet the Japanese have recently demonstrated improvements in the dexterity, flexibility, and compliance of robotic manipulators.[61] U.S. engineers have made important gains in applying the techniques of artificial intelligence to robotic applications.[62] If an integrated A&R program were given sufficient funding, attention, and a common focus, the robotic devices of the early 21st century could be much more capable than those available today.

Despite numerous references in speeches and testimony to the need for robotic technologies in carrying out the exploration of the Moon and Mars, the development of robotic technologies does not receive high priority within NASA. NASA spends about $25 million yearly on applied research in artificial intelligence and robotics as part of its Space Research and Technology program (table 2-2). Yet it devotes relatively little support to A&R development in its Explo-

Table 2-2-NASA's Budget for Space Automation and Telerobotics (thousands of dollars)

	1990 Actual	1991 Budget estimate	1991 Current estimate	1992 Budget estimate
Flight Telerobotics Servicer	79,400	108,300	106,300	55,000
Telerobotics[b]	11,064	13,400	11,045	14,800
Artificial intelligence	11,069	11,800	11,189	13,100
Total	101,533	131,300	128,534	82,900

[a]FTS is funded under space station Freedom in fiscal years 1990 and 1991.
[b]Funded under CMI Space Technology Initiative in fiscal Yearn 1990 and 1991.

SOURCE: National Aeronautics and Space Administration, 1991,

[59]Garshnek, op. cit,. footnote 54, pp. 201-216.

[60]The recovery from the loss of *Challenger* cost the Nation in excess of $15 billion: U.S. Congress, Office of Technology Assessment, Access *to Space: The Future of the U.S. Space Transportation System,* OTA-ISC-415 (Washington, DC: U.S. Government Printing Office, May 1990).

[61]William L. Wittaker and Takeo Kanade, *Space Robotics in Japan* (Baltimore, MD: Japanese Technology Evaluation Center, 1991), ch. 6.

[62]James Hendler, Austin Tate, and Mark Drummond, "AI Planning: Systems and Techniques," *AI Magazine*, summer 1990, pp. 61-77.

ration Technology Program (table 2-3).[63] Prior to fiscal year 1991, NASA spent about $160 million to develop the Flight Telerobotics Services (FTS) for space station ***Freedom*** (box 2-A), previously NASA's showcase robotics program. However, in January 1991 NASA downgraded the FTS project to a technology demonstration project within the Office of Aeronautics, Exploration, and Technology. Its future is uncertain, but FTS will no longer support space station operations and maintenance.[64] NASA could improve its A&R capabilities and gather useful scientific information by carrying out modest robotics experiments on the Moon.

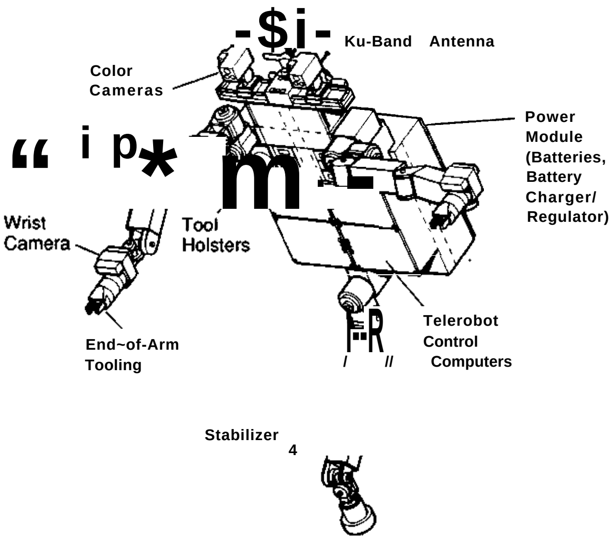

Photo credit: National Aeronautics and Space Administration

Flight Telerobotic Servicer (FTS) device originally planned for use on space station *Freedom* to service and maintain the structure. Technolcgies planned for the FTS will now be developed and demonstrated by NASA for a variety of space-based uses.

Improving the U.S. approach to A&R technologies will require the collaborative and integrated efforts of industry, academia, and government.

The United States has the capability and the resources to implement a highly competitive A&R program. However, it currently lacks the institutional structure to carry one out. In part this may result from the fact that A&R technologies were oversold in the 1980s. The technologies seemed more simple, tractable, and mature than they were. Continued technology development, and experience with successful systems, could raise public awareness of the utility of A&R systems and create a setting in which A&R engineers can be more innovative in applying them to space and Earth-bound applications.

The potential applications for A&R technologies extend far beyond the space program and include manufacturing and service industries, as well as the defense community. Three conditions

Table 2-3–NASA's Exploration Technology Program (thousands of dollars)

	1990 Actual	1991 Budget estimate	1991 Current estimate	1992 Budget estimate
Space transportation	4,145	36,000	6,000	9,000
In-space operations	1,690	23,000	2,000	
Surface operations	13,533	62,000	13,600	20,000
Human support	2,330	25,400	3,500	16,000
Lunar and Mars science	570	4,500	700	
Information systems and automation		10,500		
Nuclear propulsion		11,000	500	7,000
Innovative technologies systems analysis		5,000	1,000	–
Mission studies	5,000			

SOURCE: National Aeronautics and Space Admlnlstratlon, 1991.

[63] About $3.5 million from this budget supports A&R development in fiscal Year 1991.

[64] However, both Canada and Japan are pursuing A&R systems for use on "Freedom."

Box 2-A–The Flight Telerobotic Servicer (FTS)

In the late 1980s, NASA began a program to develop a robotic device to assist in operating, maintaining, and servicing space station *Freedom.* NASA's goals were to:

- reduce space Station dependence on crew extravehicular activity;
- improve crew safety;
- enhance crew utilization; and
- provide maintenance and servicing capability for free-flying platforms.

NASA's plans called for two test flights on the space shuttle, with delivery of the final, flight-ready article in 1995. The first test flight would test components of an FTS and would:

- evaluate telerobotic and workstation design approaches;
- correlate engineering measures of performance in space with ground simulation and with analytic predictions;
- evaluate the human-machine interface and operator fatigue; and
- demonstrate telerobotic capabilities.

The second test flight would verify the full *ITS* for space station work:

- demonstrate capability to perform space station tasks;
- test performance of dual arm manipulator and the attachment, stabilizing, and positioning subsystem;
- test performance of space station *FTS* orbiter workstation design; and
- develop and verify operational procedures and techniques.

During the congressionally mandated *Freedom* redesign in 1990 and early 1991, the *FTS* program was transfered from the space station project and is now being reconstituted as a more broadly based technology demonstration project.

NASA expects that much of the technology developed could be applied to applications in manufacturing, hazardous environments, the military, underwater, agriculture, and construction, as well as develop some basic components necessary for lunar and planetary exploration.

SOURCE: National Aeronautics and Space Administration, 1991

constrain the movement of R&D results into applications:

1. A&R R&D is spread among a number of university, industrial, and government laboratories, which by and large communicate poorly with each other about their research progress.
2. Robotics draws on the specialized knowledge of a wide variety of engineering fields; practitioners in each field are often unaware of the approaches and capabilities of another. Hence, they may not work well together. Despite some significant improvements in A&R as a result of interdisciplinary interactions, artificial intelligence and robotics are generally treated as separate disciplines rather than as one overall discipline that focuses on the development of intelligent systems to carry out a variety of well-defined tasks.
3. Existing A&R technologies currently find application only in relatively narrow industrial and government "niches," which have relatively constrained notions of what automation or robotics is. For example, manufacturing concerns make use of robots, but only of the fried-base

manipulator variety, and in a narrow range of structured tasks. Such robots cannot accommodate unstructured environments.

Because A&R derives from a widely splintered set of subfields, only in weak contact with one another, NASA has a relatively thin technology base upon which to draw for its own needs. Yet OTA's workshop participants expressed the belief that A&R technologies have high potential to make rapid advances if appropriate integrating structures or institutional mechanisms were developed. An **integrated A&R program to serve government needs for planetary exploration and assist industry should engage the capabilities of the universities, government laboratories, and industry.** Such a program might include:

- preferentially funding projects that demonstrate an emphasis on integrating the subdiscipline;
- holding workshops and conferences[65] that stress interdisciplinary sharing, especially between the science and engineering communities, as well as among the various engineering disciplines; and
- developing testbeds to demonstrate prototype technologies and making them available to a wide variety of potential users.

In addition, basic research efforts could be efficiently conducted at the universities. The universities and appropriate government laboratories could refine and demonstrate candidate technologies. Promising systems could then be handed over to development centers and various industries for final development, validation, and implementation. Such an institutional arrangement would create a relatively tight coupling between government laboratories and industry and lead to more efficient transfer into industrial applications and commercial ventures.

COST ESTIMATES

Cost estimates depend critically on the range of planned activities, their schedule, and new information developed in the course of the program. It also depends on knowing what you want to do, when you want to do it, what tools or building blocks are necessary, and what these individual components would cost. Most of these components do not exist today. Hence, it is too early to judge the total costs of an extensive program of Mars exploration that uses either robotic spacecraft or humans.

Very preliminary estimates of returning humans to the Moon and mounting crew-carrying missions to Mars suggest that costs could reach between $300 and $550 billion over a 35-year period, depending on the capabilities desired and the exploration schedule[66] Because the need to support human life in extremely harsh environments leads to large-scale technology development, exploration by human crews may cost as much as 10 to 100 times the costs of robotic exploration.[67] However, comparisons of the costs of carrying out fully robotic or crew-carrying missions can be deceiving because the two kinds of missions would likely accomplish different objectives.

Costs depend critically on the range and scale of planned activities, their schedule, and on a multitude of other factors — some well known, some only dimly perceived, and some as yet totally unrecognized. The ability to predict costs will therefore depend heavily on new information developed in the course of the program. It will also depend on the costs of developing new technologies and manufacturing new systems critical to the success of the various projects within the

[65] For example, see Donna S. Pivirotto, "Site Characterization Rover Missions," presented at the American Institute of Aeronautics and Astronautics Space Programs and Technologies Conference and Exhibit, Huntsville, AL, Sept. 25-27, 1990.

[66] General Dynamics Space Systems Division, "Lunar/Mars Initiative program Options – A General Dynamics Perspective," Briefing Report, March 1990; unpublished estimates developed by NASA for its study entitled, *Report of the 90-Day Study on Human Exploration of the Moon and Mars* (Washington, DC: NASA, November 1989).

[67] Several participants in the OTA workshop, who have experience with space systems, provided this estimate.

overall plan. Hence, OTA regards any current estimates as extremely uncertain. Actual costs could be higher or lower depending on progress made in resolving technological hurdles and in reducing the costs of developing new technologies, e.g., a heavy-lift launch system, aerobraking for capture in Mars orbit, space nuclear power, and planetary rovers.

Because the costs for any intensive program to return to the Moon and explore Mars will be high, a comprehensive search for cost-reducing methods and techniques will be of high priority.

New technologies may help to reduce the costs of exploring the Moon and Mars. For example, if miniaturized robots were able to provide sufficient capability to carry out scientific studies of Mars, they might make it possible to mount a sample return mission at relatively little cost.[68] Small robots can probably be launched on *Delta or Atlas* launch vehicles, which are available today from commercial launch service companies. Because many small robots could be sent to several different locations, they could potentially sample wider regions than a single rover collecting samples from the surface.

However, reducing costs is not just a matter of hardware, but of overall approach and management.[69] For example, where possible, it may be prudent to test major components on lunar missions in order to increase confidence in a Mars flight. Project managers of the Strategic Defense Initiative Organization Delta 180 Project, completed in 1987, found that "decreasing the burden of oversight and review, and delegating authority to those closest to the technical problems, resulted in meeting a tight launch schedule and reducing overall costs."[70] Whether these or similar techniques could lead to reduced costs in a high cost robotic or crew-carrying mission would require careful study. Nevertheless, a number of new technologies and methods, developed for use in manufacturing, may apply to the Mission from Planet Earth.[71]

The operational costs for sending human crews back to the Moon or on to Mars could be very high. As planning for the Mission from Planet Earth proceeds, it will be important for planners to examine carefully the operational costs of each project within the overall plan and determine how best to hold down operational costs.

Operational costs are notoriously hard to judge, as they depend heavily on the success engineers have in developing systems that need relatively little continuing oversight. Experience with the space shuttle[72] and with early design versions of space station ***Freedom***[73] suggest that operations costs for crew-carrying spacecraft can be extremely high. For the shuttle, operations costs grew in part because increases in estimated costs and decreases in appropriated funds caused project planners to cutback on spending for subsystems and facilities that would have controlled long-term operations costs by simplifying and automating operational tasks. The shuttle experience demonstrates that near-term cost reductions in some technologies and facilities may lead to higher long-term costs. It also suggests that operations costs can be controlled if the administration and Congress are willing to avoid the temptation to defer expenditures on facilities and new technologies in order to reduce near-term costs. By its nature, however, the development of new technologies carries with it a high degree of

[68] David P. Miller, "MiniRovers for Mars Exploration," *Proceedings of the Vision-21 Symposium,* Cleveland, OH, April 1990.

@u.s. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices,* OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[70] Ibid., p. 14.

[71] Ibid, p. 4.

[72] U.S. Congress, Office of Technology Assessment, Reducing *Launch Operations Costs: New Technologies and Practices,* OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988.

[73] William F. Fisher and Charles R. Price, *Space Station Freedom External Maintenance Task Team, Final Report* (Houston, TX: NASA Johnson Space Center, July 1990).

technological and financial risk. Therefore, new technologies may well cost more to develop than expected.

A return to the Moon and the exploration of Mars would have a major impact on NASA's yearly budget, and could adversely affect the funding of NASA's other activities.

Expenditures of $300 to $450 billion even spread over the next 30 years ($10 to $15 billion per year) would require a substantial addition to NASA's yearly space budget, which in fiscal year 1991 equals about $13.4 billion. Over 30 years, a low estimate of $300 billion would average $10 billion (in 1991 dollars), requiring an average 75-percent increase in NASA's fiscal year 1991 budget. Because yearly costs would not generally equal average costs, in some years the costs for the Mission from Planet Earth could 'be much larger than the rest of NASA's budget, and small perturbations in this funding caused by program delays or technological barriers could overwhelm other, smaller programs.[74] Hence, it maybe necessary, e.g., to scale back ambitious plans for a Mission from Planet Earth, or greatly extend the timescale for landing on Mars.

To support the Mission from Planet Earth, as well as the Mission to Planet Earth, the Advisory Committee on the Future of the U.S. Space Program recommended 10-percent annual real growth in NASA's overall budget.[75] Yet, significant pressures on the discretionary portion of the Federal budget would make obtaining a growth rate of 10 percent extremely difficult.[76]

INTERNATIONAL COOPERATION AND COMPETITION

Both international cooperation and competition are important components of a healthy, growing modern economy. As noted earlier, the United States faces a rapidly changing world in which the political and military challenge from the Soviet Union has substantially decreased but the technological and marketing capabilities of Europe and Japan have markedly increased. How the United States invests in its space program could deeply affect other segments of the economy. During the 1990s and perhaps for the first decade of the 21st century, the United States is unlikely to have any competitors in sending human crews to the Moon and Mars. However, we can expect other nations to have a strong interest in developing the technologies required for robotic spacecraft and probes, because these technologies are basic to all space activities. Many of these technologies also have a close relationship with increasing productivity in the manufacturing and service sectors and would greatly enhance later human exploration.

U.S. pursuit of an integrated program of A&R technology would contribute directly to U.S. industrial competitiveness.

Although the United States invented robots and still leads in many areas of research, in other countries robotic technologies have assumed a greater role in the economy. Canada, France, Germany, Italy, and Japan have targeted A&R technologies for development. In some areas, their efforts already exceed U.S. capabilities. The experience gained in applying A&R tasks in space could assist the development of A&R technologies in other parts of U.S. industry and help it to compete in this important arena of the world economy.

Cooperative activities with other countries, if properly structured, could reduce the costs to each participant and increase the return on investment for exploration.

The U.S. space program has a long history of encouraging cooperative activities in space. As noted in an earlier OTA report, "U.S. cooperative

[74] The ongoing debate over funding space station Freedom illustrates the potential effects on smaller programs of funding a single! very large project in NASA's constrained budget.

[75] Advisory Committee on the Future of the U.S. Space Program, op.cit., footnote 3, p. 4.

[76] David Moore, statement before the Committee on Space, Science, and Technology, U.S. House of Representatives, Jan. 31, 1991. Note that 10 percent per year takes 6 years to reach 75-percent overall increase.

space projects continue to serve important political goals of supporting global economic growth and open access to information, and increasing U.S. prestige by expanding the visibility of U.S. technological accomplishments."[77] Cooperative projects also require significant coordination among member nations and cost more overall. Although many cooperative projects have achieved significant scientific success, some, e.g., Ulysses[78] and the international space station ***Freedom,*** have demonstrated that the management of large cooperative projects may encounter significant financial and other hurdles.[79]

A return to the Moon and an exploration of Mars present a range of possible cooperative activities with other nations. Because the costs for intensive planetary exploration are likely to be very high, even for projects that do not require human crews on the Moon or Mars, international cooperative activities could reduce costs to each participant and increase the overall return on investment for exploration. Total program costs are likely to be higher, however, because of the increased cost burden from coordination and management. Yet, except for the Soviet Union, other countries have demonstrated relatively little interest in sending human crews to the Moon or Mars.[80] Based on demonstrated international interest, robotic missions present the strongest opportunities for the United States to initiate cooperative missions, for at least the next decade. All three major space-faring entities — ESA, Japan, and the Soviet Union — might be interested in participating. The Soviet Union has already offered to contribute to a joint project. Just as competition with the Soviet Union to reach the Moon served U.S. cold war goals, cooperation with the Soviet Union today is consistent with our current policy of including them in the family of nations. If the Soviet Union can survive its current economic and political crises, during the early part of the next century, cooperation with the Soviet Union on sending human crews to and from Mars might be attractive.

For example, the Soviet Union has much greater experience than the United States with supporting crews for long periods in space and has conducted numerous experiments in life sciences. **Cooperation with the Soviet Union could markedly reduce U.S. expenditures for life sciences research, which would be extremely important in understanding and reducing the risks of extended spaceflight.**

Japan[81] and Canada[82] have made significant advances in certain areas of A&R germane to space activities. **Entering into a cooperative program to study some of the basic issues of robotics could enhance U.S. progress in developing robotic systems for our space program and for other areas of U.S. industry. By cooperating on basic and preapplication research issues,83 all partners could advance their own abilities to apply this research to areas of specialized interest, both within the space program and beyond.**

The benefits of international cooperation are closely tied to the methods of implementation.

[77] U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in U.S. Civilian Space Activities,* OTA-ISC-239 (Washington, DC: U.S. Government Printing Office, 1985), p. 7.

[78] Ulysses, a project to examine the magnetic fields and other aspects of the solar system far above and below the plane of the solar system, was to have involved two spacecraft, one supplied by the United States and one supplied by the European Space Agency. The project nearly failed in February 1981 when the United States unilaterally withdrew funding for its spacecraft.

[79] See Joan Johnson FreeSe, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co., 1990), chs. 7 and 13.

[80] Some Japanese space officials have expressed interest in sending human crews to the Moon, but this interest has not Yet been translated into substantial funding support.

[81] William L. Wittaker and Takeo Kanade, *Space Robotics in Japan* (Baltimore, MD: Japanese Technology Evaluation Center, 1991).

[82] NASA Advanced Technology Advisory Committee, "Advancing Automation and Robotics Technolgy for the Space Station *Freedom* and for the U.S. Economy," Technical Memorandum 103851 (Washington, DC: Ames Research Center, National Aeronautics and Space Administration, May 1991), app. C.

[83] & new technologies find their way into industrial or consumer applications, fewer firms wish to share information, as it has a direct bearing on the firm's competitive position.

Experience with other cooperative ventures in space show that to keep costs under control, the planning and engineering interfaces must be kept as simple as possible.[84] The cooperative efforts to study Comet Halley in the mid 1980s worked well, in large part, because the cooperating entities[85] contributed individual projects that each would have pursued even without a cooperative program. Some cooperative projects might require joint development or much closer working relationships than were necessary in studying Comet Halley. Nevertheless, efforts to keep project management as simple as possible should result in more cost-effective results.

The following examples present a few potential cooperative ventures that might contribute to increased U.S. competitiveness and/or U.S. leadership in science and engineering. They represent only a small sample of the range of activities that are possible:

- ***Life sciences research —*** Cooperating on life sciences work with the Soviets could be highly fruitful for both parties. Soviet scientists are now willing to share more of their data on weightlessness and other life sciences issues and NASA is cooperating with the Soviet Union in a variety of life sciences research, including taking standardized measurements with U.S. equipment onboard Mir, and exchanging biological specimens. However, the two countries could extend their opportunities to collect high-quality human data. For example, the United States and the Soviet Union could fly joint long-term missions on the Mirspace station, using U.S. life sciences and data-recording technology.
- ***Astronomy from the Moon –*** Making astronomical observations from the Moon might be an especially fruitful area in which to cooperate, at several levels. The major space-faring nations also have strong programs in astronomy and would likely have an interest in cooperating on designing and placing observatories of various sizes on the Moon. Such a program could even involve countries that lack an independent means to reach the Moon.
- ***Small rovers on the Moon or Mars —*** Rovers are roving instrumental platforms that can extend vision and other human capabilities to distant places. Several small rovers[86] could be developed and then launched on a single booster. Each cooperating entity could build its own small rover, specialized to gather specific data. The redundancy provided by having several robotic devices, independently designed and manufactured, could increase mission success. Here again, each country could contribute according to its own capabilities.
- ***Use of Soviet Energia — The*** Soviet Union possesses the world's only heavy-lift launch vehicle, capable of lifting about 250,000 pounds to low-Earth orbit. It has offered to make ***Energia*** available to the United States for launching large payloads. In the near term, the Soviet offer could assist in developing U.S. plans to launch large, heavy payloads, e.g., fuel or other noncritical components of a Moon or Mars expedition. If these cooperative ventures succeeded, they could be extended to include the use of Energia to launch other payloads.
- ***Cooperative efforts in network projects —*** Europe and the United States are both exploring the use of instrumental networks on Mars to conduct scientific exploration. Each cooperating entity could contribute science payloads, landers, or orbiting satellites to gather data for a joint network project.

[84] Joan Johnson-Freese, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co., 1990), ch. 15.

[85] The European Space Agency, Japan's Institute of Space and Astronautical Sciences, NASA, and the Soviet Union's Space Research Institute.

[86] The terns minirover or microrover are often used to denote robotic rovers that range from about a meter down to several centimeters in overall length. Neither term has a precise definition and are often used interchangeably. This report uses the general term small rover.