Human Exploration of the Moon and Mars

RATIONALE FOR HUMAN EXPLORATION OF THE SOLAR SYSTEM

Should the United States spend public dollars to return to the Moon? Should it consider sending humans to explore Mars? Throughout the latter 20th century, various individuals and groups have urged the establishment of programs to explore the Moon and Mars[1] or other solar system components. They have based their arguments on one or more of the following propositions:

1. establishment of a permanent lunar base or human exploration of Mars would return the United States to a preeminent position in space activities;
2. humans have a fundamental desire to explore the unknown;
3. exploration of Mars would improve U.S. competitiveness;
4. exploration of Mars would vastly improve scientific understanding of the solar system and the Earth; and
5. human exploration of Mars would return other indirect benefits to U.S. society.

1. ***Establishment of a permanent lunar base or human exploration of Mars would return the United States to a preeminent position in space activities.*** Proponents of this proposition argue for a return to the Apollo goal of U.S. preeminence in space activities across the board in order to demonstrate to the rest of the world and to ourselves that Americans have both the capacity and the will to pursue ambitious technological goals.[2] In this view, demonstrating U.S technological prowess by pursuing a challenging, highly visible goal would result in considerable global geopolitical advantage for the Nation and a return to engineering excellence.

In calling for the United States, to "commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to Earth,"[3] President John F. Kennedy in 1%1 explicitly sought to use the technological capability of the Nation to establish supremacy in space activities, thereby demonstrating the superiority of the U.S. political and economic system.[4] Then America's primary political and economic competitor was the Soviet Union, which, in orbiting Sputnik in 1957 and cosmonaut Yuri Gagarin in 1%1, revealed a surprising level of Soviet technological capability. The Apollo program was successful in demonstrating to the rest of the world that the United States was able to pursue and meet demanding technical challenges.

The global setting for space activities has changed considerably from the days of Apollo when the United States won the race to reach the Moon ahead of the Soviets. The Soviet Union faces major economic and political challenges from within; its allies in Eastern Europe are moving rapidly, if uncertainly, toward market economies and have cut back substantially on military funding. In order to support the movement of the

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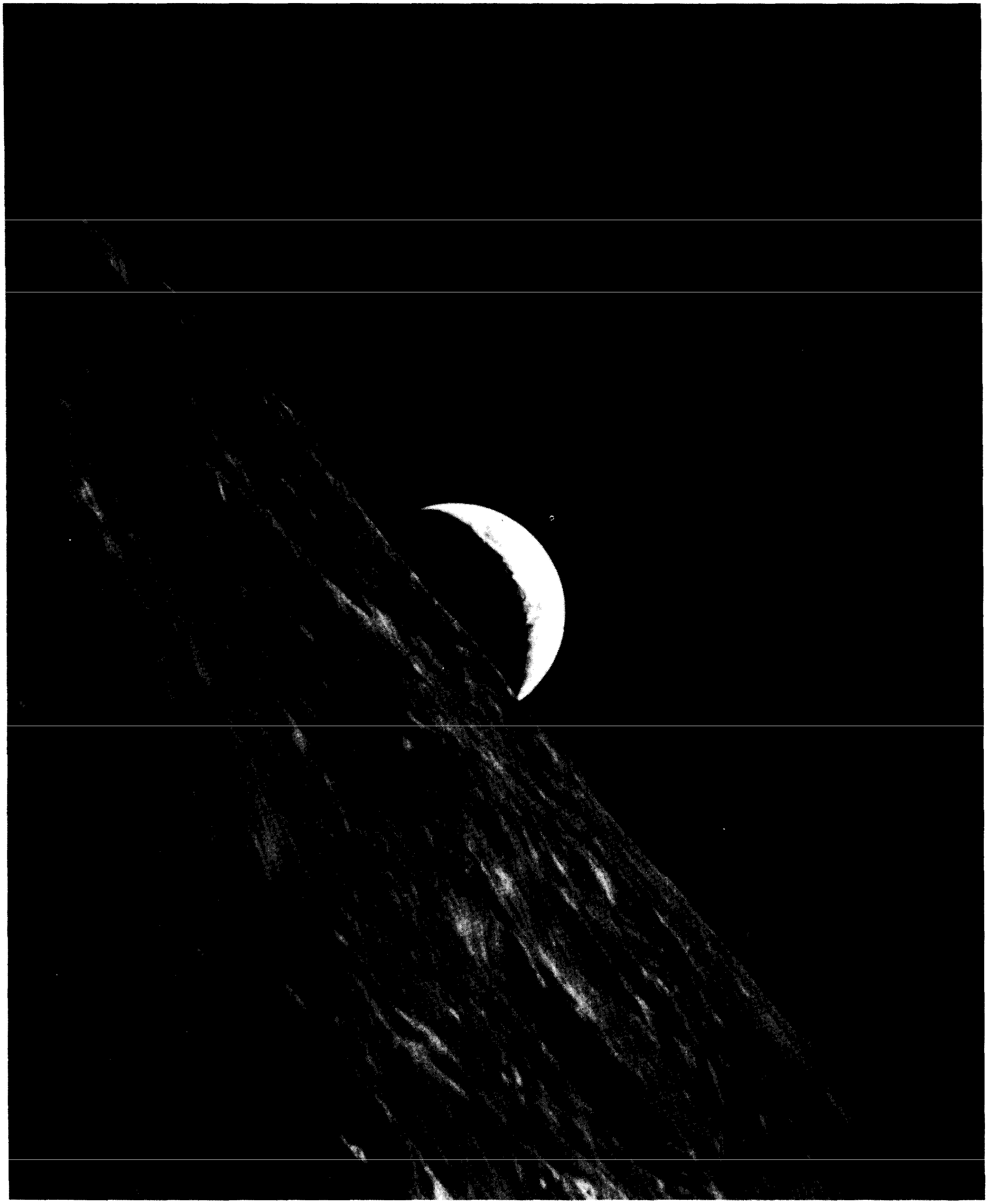
[1]One of the earlier attempts t. popularize the exploration of Mars was contained in a series of articles in *Colliers* in 1952. In that series, Wernher von Braun, who had helped design the German V-2 rocket and later became the director of NASA's Marshall Space Flight Center, proposed building a large, rotating space station in preparation for a journey to Mars. See also, Wernher von Braun, *The Mans Project* (Champaign, IL: University of Illinois Press, 1991).

[2]National Commission on Space, *Pioneering the Space Frontier: The Report of the National Commission on Space* (New York, NY: Ballantine, 1986), pp. 5-21.

[3]John F. Kennedy, Speech to a joint session of Congress, May 25, 1961.

[4]U.S. Congress, Office of Technology Assessment, *Civilian Space Policy and Applications,* OTA. STI-177 (Washington, DC: U.S. Government Printing Office, 1982), pp. 35-36.



Ph credit: Na A utics and Sp e Adm

Cresce Earth abo th ar fars d P otograp tak from Apo Command Mod e abo the Moo former Warsaw Pact allies toward economic stability and growth, the United States has adopted a posture of cooperation in political and economic affairs. For example, during the recent Gulf War, the United States took special care to include the Soviet Union in discussions and decisions regarding U.S. and United Nations intervention. In the recent past, the MidEast has been more an arena for political competition than cooperation with the Soviet Union.

These new events raise the question whether the United States should demonstrate its leadership by human exploration. In the United States other scientific and technical challenges in our national and global agenda, e.g., that of protecting Earth's atmosphere, oceans, and continents from anthropogenic degradation, have assumed greater importance than competing with the Soviet Union in space. It may be, for example, that the United States could better demonstrate technological leadership by tackling and solving major environmental challenges, e.g., the deterioration of the global atmosphere. In recent years, Congress has consistently funded a space program that supported study of the solar system and the universe, Earth's environment, and human exploration, in the belief that all these thrusts, if appropriately balanced, could assist in developing U.S. technological capabilities and demonstrate to the world U.S. leadership in advanced technologies.[5]

2. ***Humans have a fundamental desire to explore the unknown.*** Some proponents of vigorous exploration missions to Mars base their argument on a perception that sending humans to Mars would satisfy a basic human desire to explore, to push beyond known boundaries,[6] to satisfy our curiosity. These arguments appeal to the imagination and are particularly strong in the United States, where the westward expansion of the last century provides ready metaphors.[7]

These metaphors speak to strongly held notions about the West, supported by the media and popular literature. However, as some historians and folklorists have noted, the use of these metaphors stems from an uncritical view of historical events, and often fail when subjected to analytical scrutiny. Settlement of the western frontier, while contributing to the development of a strong Nation, was also fraught with failures and left many unresolved issues that are still with the Nation.[9] Furthermore, these metaphors are not necessarily shared by all societies. As the historian Stephan Pyne notes, "We explore not because it is in our genetic makeup but because it is within our cultural heritage."[10] In Europe and Japan human exploration of the solar system receives proportionately much less support than in the United States. Japan's and Europe's programs tend to emphasize space science and applications pursued robotically.[11]

Japanese proponents of human spaceflight have urged increased funding for human spaceflight, but with little success. Major attention to human spaceflight would require a concomitant increase in its yearly space budget to develop an adequate launch system[12] and other infrastructure elements for human spaceflight, yet its space budget for both the National Space Development

[5]Sally K. Ride, *Leadership and America's Future in Space* (Washington, DC: National Aeronautics and Space Administration, August 1987), pp. 11-14.

[6]Arnold D. Aldrich, NASA Office of Aeronautics, Exploration and Technology, "The Space Exploration Initiative," presented to the American Association for the Advancement of Science Symposium on the Human Exploration of Space, Feb. 17, 1990, pp.2-3.

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

[8]Beverly J. Stoeltje, "Making the Frontier Myth: Folklore Process in a Modern Nation," *Western Folklore,* vol. 16, No. 4,1987, pp. 235-255.

[9]See, e.g., Patricia Limmerick, "The Final Frontier?" Excerpted in Brian Dippie, "he Winning of the West Reconsidered," *Wilson Quarterly,* summer 1990, pp. 82-83.

[10]Stephen J. Pyne, "Space: A Third Great Age of Discovery," *Space Policy* vol. 4, No. 3, 1988, p. 189.

[11]Because both entities are interested in pursuing a balanced space program, they have also invested in programs to place humans in space, most done in cooperation with the United States.

[12]Japan is exploring the possibility of developing a space plane, HOPE, but it is to be unpiloted.

Agency and the Institute of Space and Astronautical Science has remained relatively flat as a percentage of gross national product (GNP) over the last 10 years. Japan, with the world's second largest economy, spends only 0.045 percent of its GNP on space activities, compared to about 0.18 percent for the United States.[13]

The picture in Europe varies depending on the country. Nevertheless, each country focuses most of its space investment on space science, space applications, and space transportation.[14] The same is true for the European Space Agency. Although Europe has demonstrated its interest in supporting a human presence in space by contributing to space station ***Freedom*** and to developing the piloted space plane ***Hermes,*** its investment in human spaceflight is much less than U.S. investment, both in absolute dollars and as a percentage of its total budget. Europe as a whole spends about 0.11 percent of its GNP on space.

In the Soviet Union, the other nation with a strong program involving human crews, the writings of Konstantin Tsiolkovsky about the colonization of the cosmos served as inspiration to the space program. Tsiolkovsky, who wrote at the end of the 19th century, argued that although Earth provides humanity's cradle, humans cannot live in the cradle forever. Until recently, the accomplishments of the Soviet space program have been used by a succession of Soviet politicians to attempt to demonstrate the technological strength of the Soviet state and the ultimate superiority of the Communist political system. Today, with the failure of communism throughout Eastern Europe and the Soviet Union, and the allied concern over imminent economic collapse, political and popular support for sending humans into space has diminished significantly.[15] Although the Soviet Union plans to study Mars intensively with robotic spacecraft (e.g., the Mars '94 mission), its drive to send humans appears to have subsided.

Nevertheless, whether because of the inherent danger and challenge, or because of an age-old need to create new heroes, human spaceflight captures our interest and stimulates our imagination. For some, it provides inspiration and hope for the future. Some are drawn by the prospect of exploring, and eventually settling, new worlds.[16]

3. Exploration ***of Mars would improve U.S. competitiveness.*** Some contend that the investment in technology required to return to the Moon to stay and pursue human exploration of Mars would increase U.S. competitiveness and reinvigorate the U.S. economy.[17] Today, the United States faces commercial competition for space markets from Japan and several European countries. China and the Soviet Union have also entered the launch vehicle market with capable launchers.[18]

However, it is not clear that investments in the technologies to support human exploration, which must be supported primarily by public funds, would necessarily contribute to the U.S. competitive position in advanced technologies. Although some technologies developed in the program would have some commercial potential, or would contribute to technological advancement in other areas, many technologies regarded as critical to the Mission from Planet Earth[19]

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[13]Damon R. Wells and Daniel E. Hastings, "A Comparative Study of the U.S. and Japanese Space programs," *Space Policy, in* press.

[14]George D. Ojalehto and Richard R. Vondrak, "A Look at the Growing Civil Space Club," *Aeronautics and Astronautics,* February 1991, pp. *12-16.*

[15]For example, the Soviet *Government has* slowed development of the Soviet shuttle, *Buran*, and scaled back plans for a larger version of the Soviet space station, *Mir.* Personal communication, Roald Sagdeev, 1991; Nicholas L. Johnson, *The Soviet Year in Space 1990* (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), pp. 98-122.

[16]See the discussion in Donald P. Hearth (cd.), *Why Man Explores* (Washington, DC: U.S. Government Printing Office, 1977).

[17]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/February 1991, p. 14.

[18]U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities, OTA-ISC-239* (Washington, DC: U.S. Government Printing Office, 1985), ch. 4.

[19]Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (Washington, DC: U.S. Government Printing Office, December 1990), pp. 30-31.

have little use outside it. For example, the heavy-lift launch vehicle is one of the primary technologies needed to support human exploration of the Moon and Mars.[20] Yet a commercial market for heavy-lift launchers is unlikely for decades. Government use would likely be limited to resupply of a space station and sending people to the Moon or Mars.[21] The Soviet Union has been trying to market its heavy-lift launcher, ***Energia,*** for several years[22] with no success.

Aerobraking, nuclear propulsion, space-based engines, and space nuclear propulsion and power, which might be critical to Mars exploration (figure 3-1), and which would be costly to develop, have relatively few applications or market outside

Figure 3-1 –Summary of Possible Expiration Technology Needs (Including Robotic and Piloted, Lunar Mars Missions, and Possible Secondary Applications to Other Space Science Missions)

technology THRUST	TECHNOLOGY PROGRAM AREA	Lunar Outpost ROBOTIC	Lunar Outpost HUMAN	Mars Exploration ROBOTIC	Mars Exploration HUMAN	Other Solar System Expiration Applications
Earth-To-Orbit	Propulsion~ Avionics, Manufacturing		●	⊖	●	◒
Space Transportation	Aerobraking		●		●	◒
	Space-Based Engines		●	⊖	●	⊖
	Autonomous Landing		◒	◒	◒	◒
	Auto. Rendezvous & Docking		⊖	◒	◒	◒
	Vehicle Structures & Cryo Tankage		⊖	⊖	◒	⊖
	Artificial Gravity				◒	
In-Space Operations	Cryogenic Fluid Systems		◒		◒	
	In-Space Assembly & Construction		◒		◒	⊖
	Vehicle Servicing & Processing		◒		◒	⊖
Surface Operations	Space Nuclear Power	◒	●	⊖	●	◒
	in Situ Resource Processing		●	⊖	●	
	Planetary Rover	◒	◒	◒	◒	◒
	Surface Solar Power	⊖	◒	⊖	◒	◒
	Surface Habitats & Construction		◒		◒	
Human support	Regenerative Life Support		●		●	
	Radiation Protection		●		●	
	Extravehicular Activity Systems		◒		◒	
	Exploration Human Factors		⊖		⊖	
Lunar & Mars Science	Sample Acq. Analysis, & Preserv.	◒	⊖	◒	⊖	◒
	Probes & Penetrators			◒	⊖	◒
	Astrophysical Observatories		◒			⊖
Information Systems & Automation	High-Rate Communications	⊖	⊖	◒	◒	◒
	Exploration Automation & Robotics	◒	◒	◒	◒	◒
	Planetary Photonics	⊖	⊖	◒	⊖	⊖
	Exploration Data Systems	⊖	⊖	◒	◒	◒
Nuclear Propulsion	Nuclear Thermal Propulsion				●	◒
	Nuclear Electric Propulsion				●	◒

⊖ High-Leverage Technology ◒ Enabling for Some Expiration System Options ● Critical Exploration Initiative Technology

NOTE: The symbols under each technology represent NASA' s assessment of the relative importance of the technology to the space exploration initiative. However, that assessment and the schedule of development depend critically on the particular exploration scenario chosen.

SOURCE: National Aeronautics and Space Administration, Space *Exploration Initiative Technology Needs and Plans: A Report to the* United States *Senate* Committee *on Appropriations Subcommittee* on ttre Veteran's *Administration,* Housing and Urban Development, and *Independent Agencies* (Washington, DO: NASA, summer 1990), p. 3-3.

[20] 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, 1990), p. 24.

[21] Ibid.

[22] Stephane Chenard, "Restructuring the Soviet Space Industry," *Space Markets,* May 1990, pp. 231-236.

of the Mission from Planet Earth. Others, such as avionics, regenerative life support, and radiation protection would have applications either on Earth or in low-Earth orbit, and could contribute to U.S. competitiveness. Yet, investments in technologies for Mission ***to*** Planet Earth, or for robotics exploration, are likely to have much greater relevance to the wider American economy, and contribute to U.S. competitiveness with other nations.

4. Exploration ***of Mars would vastly improve scientific undemanding of the solar system and the Earth.*** Many observers have noted that the scientific knowledge gained from a sustained exploration program would assist in understanding the properties of Earth's atmosphere, oceans, and continents.[23] As explained elsewhere in this report, such exploration could help resolve questions regarding the presence of life past or present on Mars, and assist in understanding the long-term evolution of Mars. Questions regarding the origins of life command particular interest, as they relate to the foundations of the human condition.

5. ***Human exploration of Mars would return other indirect benefits to U.S. society.*** Some argue that the preparations required for sending human crews to and from Mars would capture public interest and spark a revival of interest in the study of mathematics, science, and engineering. They point out, for example, that the Smithsonian National Air and Space Museum has the highest visitation rate of any museum in the world. However, whether such curiosity translates to substantially greater interest among America's young people in pursuing the study of technical subjects has not been demonstrated. As the experience with the Apollo program showed,[24] some percentage of the population will be drawn to devote their life's work to science and technology through encounters with the U.S. space program. However, without accompanying major improvements, in the overall U.S. educational system including greater investment, such interests may not be adequately supported.

The above discussion summarizes several propositions concerning the human exploration of the solar system, and raises questions about the conclusions one could draw from their use. Although proponents often cite one or more of these propositions, they have not been sufficiently analyzed or tested in public or scholarly debate. A survey of the literature on human exploration of the solar system reveals that proponents of expanding the presence of humans beyond Earth orbit have generally relied on the sum of several arguments to support their case.[25] Ultimately, the argument for human exploration of the solar system rests heavily on the proposition that some proportion of humans will eventually wish to establish a home elsewhere in the solar system. Many proponents of a Mission from Planet Earth suggest that such an effort would prepare us for that eventuality.

Although these arguments carry weight in the decisions to explore the solar system, ultimately the broad political process will shape the course of investment in exploration programs, here and abroad, and will include other considerations, e.g., competing demands on the Federal purse. However, the political process is likely to be incapable of allocating resources appropriately if initial cost estimates are incorrect; commitments on capability, schedule, and costs are ignored; and no one is held accountable for cost and schedule growth. In other words, enforcement of performance as promised is central to making the political process work efficiently.

[23] Carl Sagan and *Richard Turco, Where No Man Thought: Nuclear Winter and the End of the Arms Race (New* York, NY: Random House, *1991),* App. C. They point out that research on the consequences to the world's climate of a major nuclear war, the so-called nuclear winter, came about in part because planetary researchers were attempting to understand the evolution of the atmospheres of Venus and Mars.

[24] Thomas Die@ Laura Lund, and Jeffrey D. Rosendhal, "On the Origins of Scientists and Engineers," Publication of the Space Policy Institute, George Washington University, Washington, DC, April 1989.

[25] See, e.g., Harry L. Shipman, ‘‘*mans* in *Space: 21st Century Frontiers (New* York, NY: Plenum Press, 1989), part I.

RISKS TO HUMAN LIFE IN SPACE

Permanent habitation on the lunar surface or the exploration of Mars would expose humans and other living beings to a wide variety of risks, including possible radiation damage from cosmic rays and solar flare particles and atrophied muscles and loss of bone calcium[26] resulting from extremely low gravity.[27] These risks will have to be understood and mitigation procedures and technologies developed before it will be considered sufficiently safe to commit to such missions. Tables 3-1 to 3-5 summarize the risks to health that crews could experience under different scenarios.

In addition to these physiological risks, crews would also be subject to considerable psychological stress as a result of living for long periods of time in highly controlled, artificial environments. Explorers of earlier eras, though they may have faced loneliness and even cramped traveling conditions, have nevertheless been able to breathe the surrounding atmosphere and walk the Earth or sail the seas in direct contact with their natural environment.[28] Preparing for a Mars expedition would require study of the effects of such environments on the human psyche. It would also require extensive training in order to reduce or mitigate negative psychological effects.

Launch into orbit, travel in space, and return to Earth present additional risk to humans and robots. However, because robots are expendable and can be replaced, their loss is of much less concern than the loss of humans. If the United States wishes to send people into space on a routine basis, it will have to acknowledge and accept the risks of human spaceflight. NASA should exert its best efforts to ensure flight safety but also prepare the public for handling further losses that will likely occur.

THE HUMAN-ROBOTIC PARTNERSHIP

The debate over the exploration of the Moon and Mars is often framed as humans v. robots. Some scientists fear that sending humans to these two celestial bodies might preclude the pursuit of high quality science. On the other hand, some proponents of human exploration evince concern that doing as much science as possible robotically would diminish interest in sending humans. Nevertheless, humans will always be in command. At question is, where would they most effectively stand?

Most participants in OTA's workshop, which was composed of planetary scientists as well as experts in robotics and other disciplines, felt that humans would eventually return to the Moon and reach Mars. Although participants reached varied conclusions regarding the desirability of sending humans, they generally eschewed arguments presented in either/or terms. Rather, participants framed their discussion in terms of the relative strengths of humans and robots in exploring the Moon and Mars. In their view, exploration should be thought of as a partnership to which robots and humans each contribute important capabilities.

For example, robots are particularly good at repetitive tasks. In general, robots excel in gathering large amounts of data and doing simple analyses. Hence, they can be designed for reconnaissance, which involves highly repetitive actions and simple analysis. Although they are difficult to reconfigure for new tasks, robots are also highly predictable and can be directed to test hypotheses suggested by the data they gather. However, robots are subject to mechanical failure, design

[26] Researchers believe that the body recovers fairly quickly from muscle atrophy, but are unsure about the recovery from loss of bone calcium.

[27] The use of artificial gravity on the long journey to and from Mars, or the use of nuclear propulsion, which could significantly shorten it, might circumvent some problems with near zero gravity.

[28] A clear exception, of course, are the many undersea explorers who, for short periods, have lived in comparatively cramped conditions in artificial environments.

and manufacturing errors, and errors by human operators.

People, on the other hand, are adept at integrating and analyzing diverse sensory inputs and in seeing connections generally beyond the ability of robots, particularly when responding to new information. Humans can respond to new situations and adapt their strategies accordingly. Only humans are adept at field science, which demands all of these properties. In the view of several workshop participants, humans would have a clear role in doing geological field work on both celestial bodies and in searching for life on Mars.

Humans are also less predictable than robots and subject to illness, homesickness, stress from confinement, hunger, thirst, and other human qualities. They would need protective space suits and pressurized habitats on both the lunar and Martian surface. Hence, they require far greater and more complicated support than robots.

Placing humans on Mars might lead to a contamination of the Mars environment,[29] complicating the search for indigenous life that might exist in special ecological niches.[30] Conversely, returning humans or soil and rock samples from Mars might contaminate species on Earth, although scientists regard the possibility as extremely remote. Because of these possibilities, however remote in practice, the United States and other signatories to the ***Outer Space Treaty*** agreed that "State Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose."[31] The initial use of robotic devices, operated by humans on Earth, would make much less impact on the planet than humans and their associated life-support infrastructure, and, as noted, could provide advance information to lessen potential human impacts. In particular, robotic devices could return samples from Mars in such a way that they could be carefully controlled and prevented from contaminating Earth.

The workshop concluded that if humans travel to Mars, their primary role should be to pursue scientific studies. They also concluded that beyond noting the relative strengths and weaknesses of robots and humans in scientific studies, it is too early to assign specific tasks to each through the sequence of exploratory phases. The workshop further concluded that scientists will need to learn more about the planet to determine what robots, and then humans with robots, should do. The relationship between robots and humans is a flexible one, that can shift substantially as more is learned. As robots become increasingly more capable, they can assume tasks now thought too difficult. Improvements in robotic capacity would improve human output as well.

The Moon presents a somewhat different case because it is much closer than Mars. On the one hand, because of the proximity of the Moon, automation and robotics (A&R) engineers can readily overcome the time delay problems they would face in attempting to operate robots at more distant locations. This fact could allow a much more intensive use of teleoperated systems to explore, prospect, experiment with building surface structures and instruments, and operate simple laboratories and observational instruments. Yet because the Moon is closer, it is also technically easier and therefore cheaper to put human crews on the lunar surface than on Mars. Hence, there will remain a great interest in putting people back on the Moon even if robotics engineers develop very capable robotic devices, because some see a permanent base on the Moon as a stepping stone to Mars.

[29] Although machines can also contaminate new environments, the space agencies make significant attempts to sterilize them before launch.

[30] D.L. De Vincenzi, "Planetary Protection Issues and the Future Exploration of Mars," *Advances in Space Research, December* 1990.

[31] United *Nations, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and other Celestial Bodies, 18* UST 2410, Article IX.

Because scientists already know more about sending humans to the Moon than to Mars, the amount of information required from science missions before establishing a human base is far less. However, as noted in the next chapter, the additional data provided from further robotic study of the Moon would reduce risks to humans, and increase their productivity.

Contamination is an issue on the Moon, as large-scale activities that include lunar bases and possibly manufacturing could generate an atmosphere greater than the Moon's existing atmosphere.[32] Not only would such an artificial atmosphere adversely impact scientific study of the Moon's atmospheric sources and sinks, the generation of gases near astronomical observatories could affect their operation.

credit: Na Aero utics and Spa Adm

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ROBOTICS SUPPORT OF LUNAR EXPLORATION AND UTILIZATION

If the United States decides to establish a lunar base, A&R technologies would provide critical support to science both prior to sending human crews and after they are on the surface. The partnership between humans and robots could accomplish much more on the surface than humans alone could achieve. In both phases, the lunar surface could provide an important testing ground for A&R technologies that would be used on Mars.

Robotic exploratory missions could:

1. ***Advance the basic scientific knowledge of the structure and evolution of the Moon (composition, geology, geophysics, atmosphere) —*** Although scientist have gathered significant data about certain aspects of the Moon, the recent lunar observations from the ***Galileo*** spacecraft[33] have demonstrated scientists' overall knowledge of the lunar surface is surprisingly thin. Detailed survey from orbit with advanced sensors (unavailable in the Apollo days) would enhance the scientific results from human crews should they reach the surface. Robotics Lunar rovers could, for example, explore areas of the Moon that might contain trapped water in advance of placing human crews on the lunar surface.

2, ***Assist in selecting landing sites for crews —*** Considerable data on potential landing sites on the lunar nearside already exist from Apollo results, yet additional data on the elemental and mineralogical content, compositional diversity, and surface mor-

[32] Richard R. Vondrak, "creation of an Artificial Lunar Atmosphere," *Nature*, vol. 248, No. 5450, Apr. 19, 1974, pp. 657,659.

[33] See the extended abstracts published in *Lunar and Planetary Sciences*, vol. 22, Lunar and Planetary Institute, Houston, TX, 1991: Belton et al., pp. 83-84; Head et al., pp. 547-548; McEwen et al., pp. 871-872; Pieters et al., pp. 1067-1068.

phology for a wide variety of potential sites would be welcome to mission planners and scientists.

3. ***Test technologies to be used by human crews in working on the Moon —*** A number of technologies, particularly for construction of lunar habitats, could be tested on the Moon prior to human arrival.

4. ***Construct habitats or observatories —*** Robotic technologies could be used to construct either human habitats or even astronomical observatories and other laboratories prior to the arrival of human crews.

Robotic technologies could assist human crews on the Moon by providing:

1. ***Support for field studies —*** Detailed exploration of the Moon would require the ability to travel long distances. Robotic rovers could be used to study a variety of locations far from a lunar base. They could assist in detailed field studies using telepresence techniques to give the human operator the sense of being at the site.[34]

2. ***Emergency and logistical support –*** During an exploration mission, robot vehicles could provide support in the form of emergency assistance or even routine support for mundane tasks and logistics.

3. ***Survey of difficult or dangerous regions —*** Some regions of the Moon are likely to be particularly risky for human exploration. In such circumstances, robots would essentially act as surrogates for human explorers, and be controlled from a lunar base or from Earth.

4. ***Construction support —*** Robots could assist human crews in the construction of habitats, laboratories, astronomical observatories, and other structures.

ROBOTICS SUPPORT OF MARS EXPLORATION

If Congress and the administration agree to pursue the human exploration of Mars, robotic technologies would serve two important functions: 1) in addition to supporting the collection of scientific data, they would provide crucial advance information to increase the safety and feasibility of such exploratory missions; and 2) they would support the mission while humans are on the planet. Robotics missions would assist in meeting a set of milestones implied in President George Bush's "long-range continuing commitment" to the exploration of Mars.[35] As in the case of the Moon, the human-machine partnership would greatly extend human capabilities.

Robotic exploratory missions could:

1. ***Advance the basic scientific knowledge of the structure and evolution of Mars (geology, weather climate, etc.) —*** Mission planners would need to know a lot more about Mars in order to determine how to maximize the effectiveness of humans when they reach the planet. Robots are particularly adept at reconnaissance, and can be designed to make moderately sophisticated analytical tests of surface soils and rocks.

2 ***Reduce the risks and costs of human exploration by improving our detailed knowledge of the planet —*** Scientists have relatively poor knowledge of the surface details of Mars. Porous dusts and fields strewn with large blocks may be common.

3. ***Resolve issues of soil toxicity and other possible hazards to human safety – The*** soil of Mars in the vicinity of the Viking landers turned out to be much more reactive than had been imagined. If breathed into the lungs, Martian soil might adversely affect human health and therefore requires more study before sending humans to the planet.

[34] 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).

[35] George Bush, "Remarks by the President at 20th Anniversary of Apollo Moon Landing," The white House Office of Press Secretary, July 20, 1989.

4. ***Determine possible contamination of Mars by Earth organisms and Earth by any Mars organisms*** — If Mars does contain some forms of life, the presence of humans could contaminate them, raising ethical questions regarding the intervention of life from Earth and rendering future scientific study of Mars life forms extremely difficult. Conversely, Mars life forms, if they exist, might potentially harm life on Earth.

5. ***Refine planning for the design of human missions*** — Robotic technologies could help provide the information necessary to determine what people should do on the surface and what tools and additional robotic support they might need. If humans are to use their capacities to the fullest while on Mars, mission planners and scientists must learn as much as possible about surface conditions on Mars.

6. ***Provide data for the selection of potential landing sites 1***– Many types of landing sites exist. It would be important to select and characterize not only relatively safe landing sites, but also those of high scientific interest to maximize the special capacities of humans.[36]

7. ***Test technologies to be used by humans in landing or working on the planet*** – Numerous technologies, from aerobraking to components of habitats, could be tested by robotic devices prior to the arrival of humans.

Robotic technologies could support human exploration on Mars by providing:

1. ***Support for field studies*** – Exploring Mars insufficient detail to contribute substantially to the advancement of knowledge will require the ability to roam far and wide.[37] Robotic instruments could provide humans with greater dexterity and strength, and the ability to project their intellect far beyond their base, thus increasing human productivity and safety. They can also be provided with infrared, ultraviolet, or other sensors beyond the range of the human eye. Although machines are subject to breakdown, when operating properly they are not subject to fatigue and can carry out routine and/or repetitive tasks. Teleoperated mobile robotics devices that could survey local sites and return geological samples to a Mars base for detailed study would be of particular utility. Devices able to provide the additional sense of being at the site (telepresence) might vastly improve human productivity in detailed field studies of the Martian surface.[38]

2. ***A detailed survey before human travel*** – Prior to sending humans to a region, robotic reconnaissance vehicles could scout a path and explore points of interest for detailed human examination. These instruments need not necessarily be on the surface to be of considerable use. For example, a spacecraft orbiting Mars could be equipped to make detailed, high-resolution images of surface features of interest to scientists prior to visits by human exploration teams.[39]

3. ***Maintenance, logistical, and emergency support*** — Robotic devices could sharply reduce the amount of routine, mundane tasks human explorers would have to perform. During an exploration mission, robot vehicles could also provide emergency assistance.

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

[37] For example, if it were located in North America, the Vanes Marinaris would extend nearly from the Chesapeake Bay to San Francisco Bay. In places, this "Grand Canyon of Mars" is 16 kilometers deep and 240 kilometers wide. The volcano Olympus Mons is wider at its base than the State of Utah and over 27 kilometers high.

[38] 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); Michael W. McGreevy and Carol R. Stoker, "Telepresence for Planetary Exploration," presented at the SPIE Annual Meeting, Opticon '90," Boston, MA, Nov. 6-9, 1990.

[39] In this regard, such a spacecraft would operate much like the U.S. Landsat or French SPOT Image spacecraft, which carry sensors capable of exploring Earth's surface for minerals. Areas determined to be of particular interest can then be closely examined by field geologists.

4. ***A survey of particularly difficult or dangerous regions*** – Some regions of Mars are likely to be particularly risky for humans. In such circumstances, robots would essentially act as surrogates for human explorers.

If Congress and/or the administration decide not to pursue the human exploration of Mars in the near term, robotic exploration would nevertheless add to the growing body of scientific data about Mars and prepare the way for any future human exploratory missions. In all, it will be important to determine what is technically and politically possible and what support technologies are needed to accomplish the exploration goals. At present, scientists have only a glimmer of what is possible. For example, although scientists have suggested that telerobotic devices capable of providing a sense of presence would be highly useful,[40] they are only beginning to study how to design, build, and operate such devices effectively.[41]

STRATEGY FOR EXPLORATION

A strategy for planetary exploration will be constrained by scientific knowledge (do we know enough to design a credible work statement?), technological skills and capabilities (do we have adequate space transportation and other supporting systems?), funding (are sufficient public funds available, now and in the future, in competition with other societal needs?), and political support. Workshop participants generally agreed that the pursuit of scientific goals on Mars by itself requires no set time schedule beyond that suggested by resolution of these constraints, available launch windows, and the desire to resolve scientific questions raised by earlier missions. Future missions can be planned as data from missions already in progress are acquired and analyzed. However, several noted that political and programmatic considerations might suggest or even dictate a particular schedule – especially if the political or economic climate changed quickly. For example, when President Kennedy proposed the goal of landing a man on the Moon and returning him, he also selected a date for achieving that goal,[42] with the intention of mobilizing supportive sentiment within Congress, the public, U.S. industry, and NASA.

President Bush also proposed a date, presumably for similar reasons, by suggesting that the United States should plant the American flag on Mars by the 50th anniversary of its landing on the Moon — 2019. Many workshop participants were cautious about the goal of 2019. Although none disagreed that such a goal was technically feasible, at an unknown level of human, economic, and technical risk, many, but not all, felt that given the state of knowledge about Mars, the state of robotic technology, and our state of knowledge about human physiology in space, a specific goal is premature.[43] Scientists simply do not know enough today to assure mission planners that a crew on Mars in 2019 could accomplish a level of useful science or derive other benefits commensurate with the required investment.

If the pursuit of scientific knowledge and insight is the primary reason to explore Mars, and the most important goal of human presence on Mars, then science goals should be optimized on human missions. Proper uses of robotic technologies before and during human missions can accomplish that. A sustained program of robotics missions through the first decade of the next century to set the stage for humans if the United States decides to undertake such an enterprise.

[40] G. Geffrey Taylor and Paul D. Spudis, "A Teleoperated Robotic Field Geologist," *proceedings of Space '90 Aerospace ASCE*, Albuquerque, NM, Apr. 22-26,1990.

[41] Michael W. McGreevy and Carol R. Stoker, "Telepresence for Planetary Exploration," presented at the SPIE Annual Meeting, Opticon '90," Boston, MA, Nov. 6-9,1990.

[42] NASA officials had previously assured the president that such a goal, though ambitious, was achievable: Letter from James Webb to president Kennedy, May 1961.

[43] Several workshop participants pointed out that setting a challenging schedule, such as President Kennedy set forth for the Apollo Program, might motivate the country to achieve difficult tasks, as it did in the 1960s. As noted earlier, however, the national and international political climates are much different today than they were 30 years ago.

MANAGING THE MISSION FROM PLANET EARTH

A program to send humans back to the Moon or to explore Mars would present a formidable challenge to NASA's engineering, scientific, and management capabilities. It would also challenge the Nation's political and fiscal ability to support such a long-term, costly project.

The issue of whether to send humans to the Moon and/or Mars cannot be reduced to scientific and technological considerations alone. The funding and political support for this initiative must be provided over many Presidencies and Congresses. Experience with other large projects in NASA and other agencies suggests that the technical and managerial factors would interact strongly with short- and long-term political and budgetary concerns. These interactions will shape the success or failure of ***any*** initiative to explore space, whether carried out solely with robots, or with both robots and humans.

Lessons based on experience with the space shuttle[44] and with space station ***Freedom***[45] indicate that "success-oriented" planning and the pursuit of incompatible technical goals,[46] which leaves little room for the vagaries of the political process, may lead to much higher than expected costs, and long delays in accomplishing major technical objectives. For example, the space shuttle, which was declared operational in 1982 after four successful flights, still cannot be launched routinely.[47]

A successful strategy for exploring the Moon and Mars would include allowance for the unexpected. The lessons of the space shuttle and space station ***Freedom*** suggest that the goal of exploring the Moon and Mars could be met most effectively by developing a set of small and large 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. In the case of space station Freedom, each time the budget process resulted in lower appropriated funds for the space station, the program fell into jeopardy. Fiscal and other concerns, including engineering concerns, have made it necessary to rescope the project several times and reorganize its management structure. A more 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.
- ***A set of intermediate, phased goals structured around a common theme —*** Previous large-scale civilian space projects have had a highly structured plan with multiple and often incompatible goals.[48] The scale of the Mission from Planet Earth suggests the possibility of generating a set of interim goals with different schedules and measures of success. These interim goals would take into account the rate at which A&R technologies, as well as human capabilities, advance. Planners should resist the tendency to design a large-scale project in order to include every potential user under the aegis of a large program. Instead they should disaggregate the often incompatible goals of mul-

[44] John M. @@On, "The Space Shuttle Program: A Policy Failure," *Science,* vol. 232, May 30, 1986, pp. 1099-1105.

[45] 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).

[46] For example, in designing and promoting the space shuttle, NASA attempted to achieve the incompatible goals of piloted spaceflight and inexpensive launches in one vehicle design.

[47] Although all launch systems experience some delays as a result of mechanical failure and weather, the highly complex shuttle has proved to be much more prone to delay, in part because it carries humans. 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, 1990).

[48] Critics of the planned space station *Freedom* suggest that because it was designed to be "all things to all people," it serves 110 constituency well.

tiple constituencies, approaching the goals through multiple small programs, executed either in parallel or in series. Each project or step in the process should provide a useful product independent of the long-term goal. These steps would allow planners to learn from the successes or failures of early projects and factor these lessons into subsequent projects. The knowledge and experience gained in the early stages would allow mission planners to design a far more efficient and safe plan for human exploration than any that could be put forth today or in the near future.

- ***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.

A strategy that had these characteristics would further benefit from the following approaches:

- Optimize each project within the overall goal to achieve a single, highly focused objective.
- Where possible, make each project small enough to locate within a single NASA center in order to give it financial control of the project and to simplify management interfaces. The Exploration Office could play a coordinating role in assuring the relevance of each project to the overall goal. Robotics missions make excellent small projects because they are useful in their own right, demonstrate technology, and give project teams significant operational experience.
- Where possible, make the project's period short enough to provide results before external events undermine its rationale or support.[49]
- Decouple each project from parallel research and development projects insofar as possible within the context of achieving the overall goal, in order to provide a clean test and to clarify responsibility for success or failure.
- Select each project for its centrality to the overall mission through competition with other possible projects.

Successful management of a Mission from Planet Earth will also require stable, consistent funding, and enough of a political commitment from the administration and Congress to carry projects through the inevitable failures as well as through the successes. Congress might wish to consider multiyear funding for certain key projects of the Mission to Planet Earth in order to provide that stability and commitment.

[49] The many technical and funding challenges to be met in designing and launching large planetary probes make these projects extremely long in scope.

Table 3-1 -Medical Consequences From Exposure to Space Flight Factors (Earth Orbit Scenario)

	1 Short-Term, O-G (1-14 days) Inflight Problems	2 Postflight Problems	3 Long-Term, O-G (more than 2 weeks) Inflight Problems	4 Posttflight Problems	5 Artlficlal Gravity, 1-G (with some level of exercise) Inflight Problems	6 Postflight Problems
Mainly O-O/Reduced-Cl Effects						
Muscle Changes	Muscle strength decreased Inflight. Some muscle mass loss Indicated Has not affected mlsslon performance.	Muscle strength decreased (returning to normal In 1-2 wks). Lower extremities show Increased susceptlbllity to fatigue and reduced muscular efficiency Arm muscles show no change,	Muscle strength decreases. Fatigue noted during EVA. Muscle mass shows Indications of decrease but Is partially preserved depending on exercise regimen Inflight exercise reduces strength loss regardless of flight duration.	Increased susceptibility to muscle fatigue. Decreased leg muscle strength. Arm strength normal or slightly decreased. Loss of “muscle pump” contributes to orthostatlc Intolerance	No data Theoretically muscle strength and mass should be preserved	No data. Theoretically, postflight muscle fatigue and loss of strength should not occur.
Cardiovascular Deconditioning	Heart rate normal to slightly Increased Inflight. Isolated cases of nodal tachycardla, ecfoplc beats, and supraventricular bigemlny.	Heart rate Increased postfllght, returning to normal by one wk. Resting blood pressure decreased, Orthostatic Intolerance (susceptibility to fainting) Increased after flights longer than 5 hrs, returning to normal In 3-14 days.	Heart rate normal to slightly Increased Inflight. Diastolic blood pressure reduced. Premature ventricular beats (PVBs) and occasional premature atrial beats (PABs).	Heart rate Increased (normal by 3 wks), Decreased mean arterlal pressure. Decreased exercise capacity Recovery time related to Inflight exercise, rather than flight duration Orthostatlc tolerance returning to normal by 3 wks. Unifocal PABs and PVBs.	No data, Theoretically, normal cardiovascular function should be preserved	No data. Theoretically, postflight cardiovascular problems, Including orthostatic Intolerance, should not occur.
Bone Loss, Hypercalclurta	Increasing negative calcium balance Inflight.	0s Calcls (heel bone) density decreased Little or no loss from non-weightbearing bones,	Increased potential for kidney stones, Hypercalcluria plateaus after 1 mo. Calcium balance becomes more negative throughout flight,	Decreased density of weightbearing bones. Recovery time approx. same as flight time. Neg. calcium balance (recovery several wks,	No data. Theoretically, bone Integrity should be preserved. Hypercalciuria should not occur. Potentlal for kidney stones should decrease.	No data. Theoretically, postflight skeletal problems should not occur
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	Body fluids shift headward causing facial fullness, feeling of head/sinus congestion. Loss of electrolytes persists throughout flight. 3% decrease In total body fluid.	Low body fluid volume contributes to orthostatic Intolerance. Conservation of fluid and electrolytes begins Immediately upon reaching gravity.	Body fluids shift headward causing facial fullness, feeling of head/sinus congestion. Loss of electrolytes persists throughout flight 3% decrease In total body fluld. (see short term)	Marked orthostatlc Intolerance from decreased blood/fluid volume. Recovery of fluid/electrolytes begins Immediately upon reaching gravity	No data With artiflcial G, major fluid shifts would not occur. Theoretically, fluid volume would be preserved. Loss of electrolytes should not occur.	No data Marked orthostatic Intolerance from decreased bloodfluid volume should not occur.
Decreased fled Blood Cell (RBC) MaSS	RBC mass begins to decrease Inflight.	RBC *mass* decreased. Recovery requires approx. 2 wks	RBC mass decreases approx. 15% during first 2-3 wks. Partlal Inflight recovery after 60 days Independent of flight duration. Possiblilty of more acute response to Injury blood loss.	RBC mass decreased. Recovery requires approx. 2 wks. to 3 mos following landing. Possibility of more acute response to Injury and blood loss.	No data. Theoretically RBC mass should not be affected, However, effects of space factore such as radiation In this scenario are unknown.	No data. Theoretically, postflight problems should not occur.
Neurological affects	Motion sickness symptoms may appear early In flight and subside/disappear In 2–7 days. Postural Illusions, sensatilons of movement, dizziness, or vertigo may Initially occur.	Postflight difficulties In maintaining postural equilibrium with eyes closed. Various vestibular disturbances maybe experienced.	Motion sickness symptoms appear early In flight and subside or disappear In 2–7 days. Postural/vestibular Illusions may Initially occur. Reappearance of Illuslins during long missions may occur.	Changes In gait, postural disequilibrium especially marked with eyes closed. Observations suggest severity proportional to flight duration and countermeasure use. Additional vestibular disturbances (dizziness, nausea vomiting) may occur.	Leaming to walk and orient In a rotating environment maybe challenging, Corlolls force may produce disorientation In certain situations. severity of problems decrease with Increasing radius of rotation.	Transition from rotating to nonrotating environments may result In vestibular and biomechanical readjustment problems Initially. Motor/ coordination patterns may need time to readjust to a nonrotating environment.

Table 3-1 -Medical Consequences From Exposure to Space Flight Factors (Earth Orbit Scenario) (continued)

	1 Short-Term, O-G (1-14 days) Inflight Problems	2 postflight problems	3 Long-Term, O-G (more than 2 weeks) Inflight Problems	4 Postflight Problems	5 Artificial Gravity, 1-G (with some level of exercise) Inflight Problems	6 postflight problems
Combined O-G-Reduced, Confinement Effects?						
Immune Changes	Although Immune system changes do occur (see post-flight problems), no serious 111-nesses have been reported In flight.	Increased number of neutro-phlls, lymphocyte numbers de-creased, returning to normal In 1-2 days. Decreased ablilty of lymphocytes to respond to challenge	Decrease In T-lymphocyte numbers with diminished reactivity and capacity for proliferation. Neutrophlls Increased Clinical significance unknown but changes may represent potential for contracting viruses, etc. from visiting crews	Recovery to normal requires 3-7 days. Clinical significance of changes unknown but may represent potential for in-creased susceptibility to Infec-tions, possibly a decreased ability to respond to Immuno-logical challenge inherent on Earth.	No data.	No data
Isolation, Confinement, Remoteness Effects						
Psychological/ Sociological	No consistent sociological problems noted Some stress may occur as a result of motion sickness or vestibular distur-bances.	Some stress may occur as a result of postural/vestibular disturbances	With Increasing duration mls-sions, potential exists for decreased motivation and pro-ductivity, compromised crew relations and coordination, and compromised crew/ground relations	Some stress may occur as a result of postural/Vestibular dis-turbances and general recov-ery timeeurse of various body systems.	Some psychological stress may occur In learning to live In a rotating environment.	Some stress may occur In tran-sitloning from a rotating to a non-rotating environment (ves-tibular and biomechanlcal readjustments)
Space Environment						
Radiation Exposure	Light flashes In eye observed (radiation striking the retina), but do not Interfere with mls-sion performance or crew health. Primary radiation source. inner radiation belt (mainly protons),	No postflight problems noted as a result of short-duration *flight* radiation exposure	Possible combined effects with O-G on physiological systems Light flashes *in eye observed* Possible tissue damage de-pending on dose and type of radiation encountered, Primary radiation source Inner radi-ation belt (mainly protons).	Increased potential for cancer Induction, cataract formation later In life depending on dose and type of radiation encoun-tered throughout mission	Artificial G has no effect on dose of radiation encountered Possibility would still exist for tissue damage depending on dose, duration, and type of ra-diation encountered	Artificial G has no effect on dose of radiation encountered Increased potential would still exist for cancer induction, cata-ract formation later in life.

SOURCE Prepared by Victoria Garshnek, References A.E. Nicogossian, CL Huntoon, and S.L Pool (ads), Space *Physiology and* Medicine, 2nd ed. (Philadelphia, PA. Lea and Febiger, 1989).

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Table 3-2- Medical Consequences From Exposure to Space Flight Factors (Lunar Outpost Mission) (3-day O-G transits, l/6-G surface stay)

	Short-Term (3-day, O-G transit) Inflight Problems	Long-Duration Surface stay (More than 2 wks at l/&-G)	(Readaptation to 1-G of Earth) Postflight Problems
Mainly 0-Reduced -Q Effects			
Muscle Changes	See column 1 table 3-1	No data. Unknown to what degree 1/6-G would enhance exercise benefits and muscle mass/strength preservation.	No data Unknown If 1/6-G combined with exercise will decrease severity of postflight muscle weakness/loss of efficiency and strength.
Cardiovascular Deconditioning	See column 1, table 3-1	No data Unknown to what degree 1/6-G would influence cardiovascular conditioning when combined with exercise.	No data Unknown how much 1/6-G with exercise would decrease severity of Postflight cardiovascular status and severity of orthostatic Intolerance (fainting).
Bone Loss, Hypercalciuria	See column 1, table 3-1	No data. Unknown to what degree l/6-G would enhance exercise benefits for maintaining skeletal Integrity and control of hypercalciuria	No data Unknown to what degree l&G combined with exercise would preserve skeletal Integrity and decrease the potential for postflight problems (fractures, etc.)
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	See column 1, table 3-1	No data. Unknown to what degree l/6-G would Influence f!uld/electrolyte balance.	No data Unknown If 1/6G combined with exercise would decrease severity of fluid and electrolytes loss and severity of postflight orthostatic Intolerance.
Decreased Red Blood Cell Mass	See column 1, table 3-1	No data Unknown to what degree 1/6-G would Influence the partial recovery of RBC mass.	No data Unknown if 1/6-G would influence the time required for full recovery Postflight of RBC mass at l-G.
Neurological Effects	See column 1, table 3-1	No data Unknown to what degree long-duration l/6-G would Influence locomotion/mowment patterns and Coordination	No data Unknown to what degree changes In locomotlon/movement patterns and equlilibrium would occur and the amount of time needed to readjust to 1-G conditions.
Combined 0-G/Reduced-0, Confinement Effectse?			
Immune Changes	See column 1, table 3-1	No data Unknown whether long-duration 1/6 would significantly Influence the Immune system.	No data
Isolation, Confinement, Remoteness Effects			
Psychological/ Sociological	See column 1, table 3-1	No data Unknown to what degree long-term remoteness from Earth combined with a hostile/dangerous environment would Influence psychological well-being and sociological behavior.	No data
Space Environment			
Radiation Exposure	Radiation of free space (beyond Earth's protective radiation belts) encountered. No problems noted previously with Apollo astronauts although Solar Particle Events (SPE) are of concern for future missions (countermeasurea and/or shielding needed).	No data on long-term effects of free space radiation on humans. Galactic cosmic radiation and possibility of periodic solar particle events may expose crews to high energy heavy ion particles, protons, electrons, neutrons, x-rays. Effective shielding/shelter and SPE monitoring would need to be provided.	No data Increased potential for cancer Induction, genetlo mutations, and cataract formation later In life, depending on dose and type of radiation encountered.

SOURCE: See table 3-1 for reference list.

Table 3-3–Medical Consequences From Exposure to Space Flight Factors (Mars Mission) (O-G transits, l/3-G surface stay scenario)

	Long-Term, Approx. 1 yr (Conventional Propulsion) Inflight Problems	Long-Term, Approx. 6 mos. (Advanced nuclear propulsion) Inflight Problems	Long-Duration Surface Stay (More than 2 wks at l/3-G)	(Readaptation to 1-G of Earth) Postflight Problems
Mainly O-G/Reduced-Cl **Effects**				
Muscle Changes	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what degree l/3-G would enhance exercise benefits and muscle mass/strength preservation and/or conditloning after 1-year weightless flight.	No data. Severity of postflight muscle weakness/loss of efficiency and strength after 2 years of O–G unknown Beneficial effect of l/3-G exposure unknown
Cardiovascular Deconditioning	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what degree l/3-G would Influence cardiovascular condition-ing when combined with exercise after a l-year weightless flight	No data Severity of postflight cardiovas-cular status and severity of orthostatic In-tolerance (faintling) after 2 years of O-G un-known Beneficial effect of l/3-G exposure unknown.
Bone Loss, Hypercalclurla	See column 3, table 3-1	See column 3, table 3-1	No data Unknown to what degree l/3-G would enhance exercise benefits for main-taining skeletal Integrity and control of hy-percalcluria after l-yr O-G flight	No data. Potential for postflight problems (fractures, etc) unknown
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what degree l/3-G would Influence fluid/electrolyte balance after a l-year weightless flight	No data. Severity of fluid and electrolyte loss and postflight orthostatic Intolerance after 2 years of O-G flight unknown Benefi-cial effect of l/3-G exposure unknown
Decreased Red Blood Cell Ma	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what level of recov-ery l/3-G would influence RBC mass loss experienced after a 1-year weightless flight	No data
Neurological Effects	See column 3, table 3-1	See column 3, table 3-1	No data Unknown whether a l-yr O-G flight would precipitate significant post-flight disequillibrium upon reaching l/3-G and possible Interfere with Mars surface exploration activities initially	No data. Unknown to what degree changes in locomotion/movement patterns and equililbrium would occur (after 2-yrs of O-G flight and l/3-G surface stay) and time needed to readjust to 1-G Earth conditions
Combined, 0-G/Reduced-0 Confinement Effects?	See column 3, table 3-1	See column 3, table 3-1		
Immune Changes			No data Unknown whether Iongduration l/3-G would significantly Influence the im-mune system after a l-year weightless flight	No data.
Isolation, Ccnfinment, Remoteness Effects				
Psychological/ Sociological	No data Unknown to what degree long-term remoteness from Earth combined with a dangerous environment and in-creasing communication lag-time would Influence psychological/sociological behavior.	No data Unknown to what degree long-term remoteness from Earth combined ‘with a dangerous environment and in-creasing communication lag-time would Influence psychological/sociologlial behavior.	No data Unknown to what degree long-term remoteness from Earth combined with a hostile/dangerous environment and significant Earth communication lag-time would Influence psychological/soclologlca! behavior.	No data
Space Envionment				
Radiation Exposure	No data on long-term effects of free space radiation on humans. Galactic cosmic ra-diation and possibility of solar particle events may expose crew to high energy heavy Ion particles, protons, electrons, neutrons, x-rays Shleldlng/countermen-sures needed. Shelter and monitoring for SPE needed.	No data on 6-mo. exposures to free space radiation on humans. Advantage In this scenario is that crew duration/exposure is significantly reduced over the conventional propulsion scenario of 1 yr Shielding and countermeasures needed during transit. Shelter and monitoring for SPE needed regardless of shortened transit time	No data on long-term physiological effects of Mars radiation environment Galactic - cosmic radiation and possibility of periodic solar particle events may expose crews to high energy heavy Ion particles, protons, electrons, neutrons, x-rays Effective moni-toring and shleiding strategies would be needed.	No data. Increased potential for cancer Induction, genetic mutations, and cataract formation later In life, depending on dose and type of radiation encountered throughout mission

SOURCE: See table 3-1 for reference llst.

Table 3-4-Medical Consequences From Exposure to Space Flight Factors (Mars Mission)
(Artificial-G transits, l/3-G surface stay scenario)

	Artiflcial-G Transit (w/exercise) (6-12 mo. depending on Propulsion) Inflight Problems	Long-Duration Surface Stay (More than 2 wks at l/3-G)	(Artiificial-G Transit/Return to Earth) Postflight Problems
Mainly 0-G/Reduced-G Effects			
Muscle Changes	See column 5, table 3-1	No data Unknown to what degree l/3-G would Induce muscle mass or strength loss. Unknown how beneficial exercise would be to preserve adequate muscle mass and strength In l/3-G.	No data. Theoretically, return to a 1-G environment during transit should restore any loss In muscle mass or strength Induced by reduced gravity of l/3-G.
Cardiovascular Deconditioning	See column 5, table 3-1	No data. Unknown to what degree 1/3-G could Induce cardiovascular deconditioning. Unknown how beneficial exercise would be to preserve desired cardiovascular function.	No data Theoretically, return to a 1-G environment during transit should restore to normal the cardiovascular deconditioning Induced by reduced gravity of 1/3-G.
Bone Loss, Hypercalciuria	See column 5, table 3-1	No data. Unknown to what degree l/3-G would Influence bone Integrity Unknown how beneficial exercise/pharmacological measures would be In preserving skeletal status,	No data. Theoretically, return to a 1-G environment during transit should start the restoration process of any bone mineral loss Induced by reduced gravity of l/3-G.
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	See column 5, table 3-1	No data. Unknown to what degree 1/3-G would Influence fluid/electrolyte balance.	No data Theoretically, return to a 1-G environment during transit should restore any fluid/electrolyte loss induced by reduced gravity of 1/3G.
Decreased Red Blood Cell Mass	See column 5, table 3-1	No data. Unknown If l/3-G would Induce a level of RBC mass loss.	No data Theoretically, return to a 1-G environment during transit should restore any RSC mass loss Induced by reduced gravity of 1/3-G.
Neurological Effects	See column 5, table 3-1	No data. Unknown to what degree transition from rotating to non-rotating environment would influence locomotion, equilibrium, and coordination initially upon reaching the Martian surface.	No data, Unknown to what degree transition from rotating to non-rotating environment would Influence locomotion, equilibrium, and coordination upon reaching Earth"s gravity initially.
Combined 0-G/Reduced, Confinement Effects			
Immune Changes	See column 5, table 3-1	No data. Unknown whether long-duratlon 1/3-G would significantly Influence the Immune system after a 6-12 month flight In a closed environment,	No data.
Isolation, Confinement, Remoteness Effects			
Psychological/ Sociolological	No data. Unknown to what degree long-term remoteness from Earth combined with a dangerous environment and increasing communication lag-time would Influence psychological/sociological behavior.	No data. Unknown to what degree long-term remoteness from Earth combined with a hostile/dangerous environment, post-rotation neurological adjustments. communication lag-time would influence psychological/sociological behavior.	No data
Space Envionment			
Radiation Exposure	No data on long-term effects of free space radiation on humans. Galactic cosmic radiation and possibility of solar particle events may expose crew to high energy heavy Ion particles, protons, electrons, neutrons, x-rays. Shielding/countermeasures needed. Monitoring and shelter for SPE required.	No data on long-term physiological effects of Mars radiation environment. Galactic cosmic radiatlion and possibility of periodic solar particles events may expose crews to high energy heavy ion particles, protons, electrons, neutrons, x-rays. Effective SPE monitoring and shielding strategies would be needed.	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later In life, depending on dose and type of radiation encountered throughout mission.

SOURCE: See table 3-1 for reference llst.

UTable 3-5– Medical Consequences From Exposure to Space Flight Factors (Mars Mission)
(O-G and artificial-G abort scenarios)

	O-G Abort (Conventional Propulsion, 2-yrs) Inflight Problems	(Return to Earth) Postflight Problems	(Advanved-Propulsion, Approx. 1 yr.) Inflight Problems	(Return to Earth) Postflight Problems	Attn.-cl Abort (I-2 yrs, depend on propulsion) Inflight Problems	(Return to Earth) Postflight Problems ~
Mainly O-G/Reduced-G Effects						
Muscle Changes	No data.	No data.	Sea column 3, table 3-1	See column 4. table 3-1	See column 5, table 3-1	See column 6, table 3-1
Cardiovascular Deconditioning	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Bone Loss, Hypercalciuria	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	No data	No data,	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Decreased Red Blood Cell Mass	No data	No data	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Neurological Effects	No data	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Combined O-G/Reduced, Confinement Effects?						
Immune Changes	No data	No data.	See column 3, table 3–1	See column 4, table 3-1	See column 5, table 3-1	Sea column 6, table 3-1
Isolation, Confinement Remoteness Effects						
Psychological Sociological	No data on psychological and sociological aspects of a long-duration abort of a space mission.	No data	No data on psychological and socioicgical aspects of a long-duration aborted space mission.	No data.	No data on psychological and sociological aspects of a long-duratlion aborted space mission	No data. Some *stress may oc-*cur In transitioning from a rotating to a non-rotating environment (vestibular and bio-mechanical readjustments).
Space Envionment						
Radiation Exposure	No data on long-term (2-yr) effects of free space radiation on humans. Galacti cosmic radiation and possibility of solar particle events may expose crews to harmful radiation which may exceed recommended limits. Shielding, countermeasures, SPE shelter and monitoring needed.	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later In life depending on dose and type of radiation encountered throughout abort mission.	No data on long-term effects of free space radiation on humans Galactic Cosmic radiation and pessibility of solar particle events may expose crews to harmful radiation. Shielding, countermeasures, SPE shelter and monitoring needed.	No data Increased potential for cancer Induction, genetic mutations, and cataract formation later In life depending on dose and type of radiation encountered throughout abort mission.	No data on long-term (2-yr) effacts of tree space radiation on humans, Galactic cosmic radiation and possibility of solar particle events may expose crews to harmful radiation which may exceed recommended limits (especially In the 2-yr scenario). Shielding, countermeasures, SPE shelter and monitoring needed.	No data increased potential for cancer induction, genetic mutations, and cataract formation later in life depending on dose and type of radiation encountered throughout abort mission.

SOURCE: See table 3-1 for reference list