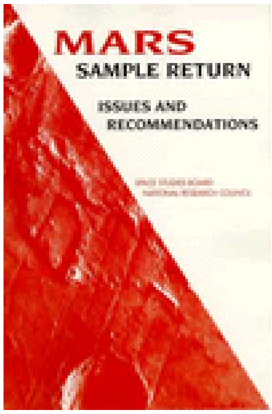

Mars Sample Return: Issues and Recommendations

Task Group on Issues in Sample Return, National Research Council

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MARS SAMPLE RETURN

ISSUES AND RECOMMENDATIONS

Task Group on Issues in Sample Return

Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Cover: This Viking Orbiter image, 200 kilometers across, shows water-worn, branching valley networks in the cratered uplands of Mars. These valleys are the main evidence for a warm wet climate on early Mars. (Photograph courtesy of NASA.)

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Preface

There has long been great interest in returning samples from solar system bodies, especially Mars. The level of scientific and public interest increased measurably during the summer of 1996 with the announcement that a naturally conveyed sample, namely, a martian meteorite found on Earth, contained circumstantial evidence of possible prior life on Mars. Studies of the meteorite also support inferences from observations of surface features that Mars once had liquid water. Since terrestrial investigations of extreme environments now indicate that primitive life appears wherever liquid water and energy are present, the meteorite results reinforce the hypothesis that life emerged on Mars, whether or not the meteorite is shown to contain direct evidence of past life there.

The present report, by the Task Group on Issues in Sample Return, addresses the question of how to ensure that any sample returned to Earth from elsewhere in the solar system has no adverse effects on our own biosphere. It complements an earlier Space Studies Board document that examined the related issue of how to keep the solar system bodies themselves clean of possible biological contamination by terrestrial spacecraft (*Biological Contamination of Mars: Issues and Recommendations*, National Academy Press, Washington, D.C., 1992), and which provided the basis for a modification of the planetary protection requirements for Mars lander missions.

Two NASA spacecraft are now on their way to Mars, beginning a new program to survey the planet and assess promising locations for sample collection. It seems likely that a sample return mission will be launched to Mars within a decade. Planning for such a mission should include consideration of the recommendations presented here.

Claude R. Canizares, *Chair*
Space Studies Board

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Executive Summary

As stated in NASA Management Instruction 8020.7, the Space Studies Board of the National Research Council (NRC) serves as the primary adviser to the National Aeronautics and Space Administration (NASA) on planetary protection policy, the purpose of which is to preserve conditions for future biological and organic exploration of planets and other solar system objects and to protect Earth and its biosphere from potential extraterrestrial sources of contamination. In October 1995 the NRC received a letter from NASA requesting that the Space Studies Board examine and provide advice on planetary protection issues related to possible sample-return missions to near-Earth solar system bodies. In response, the Space Studies Board established the Task Group on Issues in Sample Return to address the following concerns:

- The potential for a living entity to be included in a sample to be returned from another solar system body, in particular Mars;
- The scientific investigations that should be conducted to reduce uncertainty in the above assessment;
- The potential for large-scale effects on the environment resulting from the release of any returned entity;
- The status of technological measures that could be taken on a mission to prevent the unintended release of a returned sample into Earth's biosphere; and
- Criteria for controlled distribution of sample material, taking note of the anticipated regulatory framework.

The key findings and recommendations of the task group are listed below. Although focused on sample-return missions from Mars, the recommendations can be generalized to any mission that could return a sample from an extraterrestrial object with a similar potential for harboring life.

FINDINGS

• *Although current evidence suggests that the surface of Mars is inimical to life as we know it, there remain plausible scenarios for extant microbial life on Mars—for instance in possible hydrothermal oases or in subsurface regions.*

The surface environment of Mars, from which early samples are most likely to be returned, is highly oxidizing, is exposed to a high flux of ultraviolet radiation, is devoid of organic matter, and is largely devoid of liquid water. It is unlikely that life of any kind, as we currently understand it, either active or dormant, could survive in such an inhospitable environment. If active volcanism, or near-surface liquid water, is discovered on Mars, or if the subsurface environment is found to be considerably less oxidizing and wetter than the surface, the occurrence of extant life on the planet becomes more plausible.

• *Contamination of Earth by putative martian microorganisms is unlikely to pose a risk of significant ecological impact or other significant harmful effects. The risk is not zero, however.*

In the event that living martian organisms were somehow introduced into Earth's environment, the likelihood that they could survive and grow and produce harmful effects is judged to be low. Any extant martian microorganisms introduced into Earth's biosphere would likely be subject to the same physical and chemical constraints on their metabolic processes as are terrestrial organisms. Thus, extraterrestrial organisms would be unlikely to mediate any geochemical reactions that are not already catalyzed by Earth organisms. They would be unlikely to be able to compete successfully with Earth organisms, which are well adapted to their habitats.

Because pathogenesis requires specific adaptations to overcome the extensive defenses possessed by all Earth organisms, virulent extraterrestrial pathogens are unlikely. Subcellular disease agents, such as viruses and prions, are biologically part of their host organisms, and so an extraterrestrial source is extremely unlikely. Conceivably, putative extraterrestrial organisms could be capable of opportunistic infections or toxicity, as are some terrestrial bacteria, but such a risk can be eliminated by standard laboratory control procedures.

The potential for large-scale effects, either through pathogenesis or ecological disruption, is extremely small. Thus, the risks associated with inadvertent introduction of exogenous microbes into the terrestrial environment are judged to be low. However, any assessment of the potential for harmful effects involves many uncertainties, and the risk is not zero.

• *Uncertainties with regard to the possibility of extant martian life can be reduced through a program of research and exploration that might include data acquisition from orbital platforms, robotic exploration of the surface of Mars, the study of martian meteorites, the study of Mars-like or other extreme environments on Earth, and the study of returned samples. However, each returned sample should be assumed to contain viable exogenous biological entities until proven otherwise.*

A program of Mars exploration is outlined in a recent NASA strategy document, *An Exobiological Strategy for Mars Exploration* (NASA, 1995). The Space Studies Board task group strongly endorses NASA's strategy. Such an exploration program, while likely to greatly enhance our understanding of Mars and its potential for harboring life, nonetheless is not likely to significantly reduce uncertainty as to whether any particular returned sample might include a viable exogenous biological entity—at least not to the extent that planetary protection measures could be relaxed.

RECOMMENDATIONS

Sample Return and Control

Recommendation. Samples returned from Mars by spacecraft should be contained[1] and treated as though potentially hazardous until proven otherwise. No uncontained martian materials, including spacecraft surfaces that have been exposed to the martian environment, should be returned to Earth unless sterilized.

While the probability of returning a replicating biological entity in a sample from Mars, especially from sample-return missions that do not specifically target sites identified as possible oases,[2] is judged to be low and the risk of pathogenic or ecological effects is lower still, the risk is not zero. Therefore, it is reasonable that NASA adopt a prudent approach, erring on the side of caution and safety.

Recommendation. If sample containment cannot be verified en route to Earth, the sample, and any spacecraft components that may have been exposed to the sample, should either be sterilized in space or not returned to Earth.

The engineering and design of any sample-return mission should incorporate

[1]The words "contained" and "containment" are used herein to indicate physical and biological isolation.
[2]Locations that exhibit active volcanism or where the presence of liquid water is indicated.

some means of verifying sample containment during transit and prior to return to Earth. Means should also be available to sterilize the sample, and any spacecraft components that may have been exposed to it, in flight or to prevent their return to Earth in the event that containment cannot be verified.

Recommendation. Integrity of containment should be maintained through reentry of the spacecraft and transfer of the sample to an appropriate receiving facility.

The points in a mission where loss of containment is most likely to occur include operations on the martian surface; intervehicle transfer of sample material; vehicle reentry, descent, and landing; and subsequent transfer of the sample container to a receiving facility. Techniques and protocols that can ensure containment at these vulnerable points should be designed into the mission.

Recommendation. Controlled distribution of unsterilized materials returned from Mars should occur only if rigorous analyses determine that the materials do not contain a biological hazard. If any portion of the sample is removed from containment prior to completion of these analyses, it should first be sterilized.

Returned samples should be considered potentially hazardous until they have been reasonably demonstrated to be nonhazardous. Distribution of unsterilized sample material should occur only after rigorous physical, chemical, and biological analyses confirm that there is no indication of the presence of any exogenous biological entity. If any portion of the sample is removed from containment prior to this determination, it should first be sterilized. The development of effective sterilization techniques that preserve the value of treated material for other (nonbiological) types of scientific analysis should be the subject of research by NASA and by the science team associated with the sample-receiving facility.

Recommendation. The planetary protection measures adopted for the first Mars sample-return missions should not be relaxed for subsequent missions without thorough scientific review and concurrence by an appropriate independent body.

Samples returned from the martian surface, unless returned from sites specifically targeted as possible oases, are unlikely to harbor life as we know it, and there may be some pressure to reduce planetary protection requirements on subsequent sample-return missions if prior samples are found to be sterile. Presumably, however, subsequent missions will be directed toward locations on Mars where extant life is more plausible, based on data acquired from an integrated exploration program, including prior sample-return missions. Thus, planetary protection measures may become more rather than less critical as the exploration program evolves. At some point it may be reasonable to relax the requirements, but this should only be done after careful scientific review by an independent body.

Sample Evaluation

Recommendation. A research facility for receiving, containing, and processing returned samples should be established as soon as possible once serious planning for a Mars sample-return mission has begun. At a minimum, the facility should be operational at least two years prior to launch. The facility should be staffed by a multidisciplinary team of scientists responsible for the development and validation of procedures for detection, preliminary characterization, and containment of organisms (living, dead, or fossil) in returned samples and for sample sterilization. An advisory panel of scientists should be constituted with oversight responsibilities for the facility.

It was evident from the Apollo experience that the science team, and therefore the lunar receiving facility as a whole, would have been more effective if the team members had had prior experience working together as a group on common problems before receiving lunar samples. During the preliminary study of those samples, loss of containment and compromise of quarantine occurred on several occasions. Some of these occurrences might have been avoided had the science team and the receiving facility been operational well before return of the samples.

To avoid similar problems during the initial investigation of returned martian samples and to provide sufficient time to develop and validate the requisite life detection, containment, and sterilization technologies, the receiving facility and its associated science team should be established well in advance of the launch of any sample-return mission. The facility should include appropriately stringent biological containment capability and be staffed by a broadly multidisciplinary team of scientists. When fully constituted, the science team should strive to include diverse expertise in such areas as effective biological containment, geological and biological sample processing and curation, microbial paleontology and evolution, field ecology and laboratory culture, cell and molecular biology, organic and light stable isotope geochemistry, petrology, mineralogy, and martian geology.

Program Oversight

Recommendation. A panel of experts, including representatives of relevant governmental and scientific bodies, should be established as soon as possible once serious planning for a Mars sample-return mission has begun, to coordinate regulatory responsibilities and to advise NASA on the implementation of planetary protection measures for sample-return missions. The panel should be in place at least one year prior to the establishment of the sample-receiving facility (at least three years prior to launch).

Although NASA is the lead agency on matters pertaining to the exploration of space and extraterrestrial bodies, other federal agencies, such as the U.S. Department of Agriculture, may have a regulatory interest in the return of samples from Mars or other solar system objects. To coordinate regulatory and other oversight responsibilities, NASA should establish a panel analogous to the Interagency Committee on Back Contamination that coordinated regulatory and oversight activities during the lunar sample-return missions. To be effective, planetary protection measures should be integrated into the engineering and design of any sample-return mission, and, for an oversight panel to be in a position to coordinate the implementation of planetary protection requirements, it should be established as soon as serious planning for a Mars sample-return mission has begun. For the panel to be able to review and approve any plans for a Mars sample-receiving facility, the panel should be in place at least one year before the sample-receiving facility is established.

Recommendation. An administrative structure should be established within NASA to verify and certify adherence to planetary protection requirements at each critical stage of a sample-return mission, including launch, reentry, and sample distribution.

The best-laid plans are only as effective as their implementation. An internal administrative structure, with clearly defined lines of authority, is required to verify and certify adherence to planetary protection requirements at each critical stage of a sample-return mission, including launch, reentry, and sample distribution. The certification should be sequential. That is, the mission should not be allowed to proceed to the next stage until planetary protection requirements for that stage and each preceding stage have been met. For example, reentry should not be authorized unless containment has been verified or the material to be returned has been sterilized. The required internal structure is already partly in place at NASA, but the lines of authority should be more clearly specified and a certification process should be implemented for each mission stage.

Recommendation. Throughout any sample-return program, the public should be openly informed of plans, activities, results, and associated issues.

Significant changes have occurred in the public decision-making realm since the return of lunar samples during the Apollo program. More open review processes now allow for citizen involvement in nearly all aspects of governmental decision making, most notably under the National Environmental Policy Act. Scientific and technical decisions about mission hardware and operations, while still made by groups of experts, now are openly scrutinized by other governmental bodies, the general public, advocacy groups, and the media. The array of environmental and health and safety laws enacted during the past three decades often provides ample opportunity for public involvement in many parts of the decision-making process that previously were conducted in private. The possibility of legal challenges always exists.

In light of the public's past response to other controversies involving science and technology, it is possible that environmental and quality-of-life issues will be raised in the context of a Mars sample-return mission. If so, it is likely that the adequacy of NASA's planetary protection measures will be questioned in depth. The most effective strategy for allaying fear and distrust is to inform early and often as the program unfolds. Acknowledging the public's legitimate interest in planetary protection issues, and thereby keeping the public fully informed throughout the decision-making process related to sample return and handling, will go a long way toward addressing the public's concerns.

1

Introduction

In response to a request from the National Aeronautics and Space Administration (NASA), the National Research Council's Space Studies Board convened the Task Group on Issues in Sample Return to examine issues surrounding the return to Earth of samples collected from other solar system bodies. The primary impetus for the study is the planned Mars sample-return mission tentatively scheduled for launch in 2005, but the conclusions and recommendations presented in this report apply to samples returned from any solar system body with a comparable potential for harboring life. This report builds on the findings and recommendations contained in a 1992 report from the Space Studies Board, *Biological Contamination of Mars: Issues and Recommendations* (SSB, 1992), which addresses the forward contamination problem—the unintentional conveyance of terrestrial biota to Mars aboard landers sent from Earth—and contains substantial information regarding the geological and climatological history of Mars, which is not repeated here. The present report focuses on issues of potential back contamination—how to protect Earth from possible contamination by putative martian biota conveyed in a sample collected from the martian surface and returned to Earth.

The task group was asked to assess the potential for a viable exogenous biological entity being included in a sample returned to Earth from Mars, and the potential for large-scale effects if such an entity were inadvertently introduced into the biosphere of Earth. As explained in Chapters 2 and 4, the potential for either of these occurrences is judged to be low but not zero. It is worth noting that the only potential widespread threat posed by sample material returned from Mars is the possibility of introducing a replicating biological entity of nonterrestrial origin into Earth's biosphere. The amount of material to be returned is too small to pose any concern about possible toxicity, and any potential danger to researchers analyzing the samples would be obviated by standard laboratory control procedures.

Another question posed to the task group was what scientific investigations could be undertaken to reduce uncertainty regarding the possibility of extant life on Mars. This topic is addressed in Chapter 5. The task group was also asked to assess the status of technical measures for preventing the return of uncontained and unsterilized material of martian origin and, finally, to recommend criteria for controlled distribution of sample material. Technical measures that might be deployed to reduce the risk of loss of containment of sample material are discussed in Chapter 9. No attempt has been made to be comprehensive in this regard as it is recognized that NASA is a preeminent engineering organization, and its technical expertise far outstrips that of the task group.

With regard to criteria for controlled distribution of sample material, the need is clear. In order to maximize the scientific return of a sample return mission, the sample material must be distributed to research centers with particular analytic capabilities. The task group has made several recommendations (see Chapters 4 and 6) with respect to sample containment, handling, and controlled distribution. Detailed protocols for controlled distribution ultimately will be the responsibility of an oversight panel that includes representation from other federal agencies (see Chapter 8) together with the science team associated with the sample-receiving facility (see Chapter 7).

2

The Possibility of Extant Life on Mars

Although current evidence suggests that the surface of Mars is inimical to life as we know it, there remain plausible scenarios for extant microbial life on Mars—for instance, in possible hydrothermal oases or in subsurface regions.

THE CONTEMPORARY MARTIAN ENVIRONMENT

The surface of Mars today is generally inhospitable to life as we know it. It is cold, dry, and chemically oxidizing and is exposed to an intense flux of solar ultraviolet radiation.

Temperature is of interest, not only because of its controlling influence on metabolic rates but also because of its influence on the stability of liquid water. Although the peak daytime surface temperature near the equator can rise above the freezing point of water during much or all of the year, the average surface temperature is about –55°C, well below the freezing point of water.

Liquid water is essential for life as we know it, as all known terrestrial life is based on aqueous chemistry. Given our current state of knowledge in chemistry and biology, it is hard to imagine the existence of life independent of liquid water.

Water is abundant on Mars but not in liquid form (e.g., Jakosky and Haberle, 1992). Water vapor and ice crystals are present in the atmosphere. In fact, because of the cold temperature of the atmosphere, water is often saturated there or near the surface. Water ice almost certainly is present in the soil at high latitudes, where the subsurface temperatures are cold enough that atmospheric water vapor can diffuse from the atmosphere into the surface and condense as ice. Ice is present at the surface in the polar regions as well. During the half-year-long north-polar summer, the water-ice residual polar cap heats up enough to allow water to sublime into the atmosphere and be distributed globally. The polar surface temperatures are too low, however, for the ice to melt.

It is possible that liquid water may exist transiently on or near the surface in isolated pockets, although such occurrences probably are very rare. The presence of salts of the right composition and in sufficient quantity can lower the freezing point enough to allow a liquid solution to exist, although such a liquid is unstable with respect to evaporation (Clark and Van Hart, 1981). Alternatively, ice crystals trapped in closed pores in rocks or regolith grains could melt under certain circumstances, and the resulting liquid water could be prevented from evaporating by virtue of being enclosed.

Analytical experiments carried aboard the Viking landers indicated that the surface environment of Mars is highly oxidizing, although the exact nature of the oxidants was not determined (Hunten, 1979). It is possible that the martian soil contains oxidants, such as hydrogen peroxide, which are postulated to form photochemically from atmospheric water vapor and to diffuse readily into the soil. If present, such oxidants would react with, and destroy, organic molecules or biota and could be effective in sterilizing the surface environment. Their presence may be responsible for the absence of organic molecules in the soil.

The Viking lander experiments found no organic substances in the soil despite the fact that organic molecules are being added continually from meteorite impacts (Biemann et al., 1977).

The atmosphere is relatively thin, averaging about 6 millibar pressure, and consists primarily of carbon dioxide. Owing to the low concentration of atmospheric ozone, ultraviolet light from the sun can reach the surface of Mars almost unattenuated. Winter-hemisphere atmospheric ozone can absorb some of the ultraviolet, but only during a fraction of the year and only over a fraction of the planet. The attenuation is much less than that due to the ozone layer on Earth. Thus, throughout the martian year the entire surface of the planet is subject to an intense flux of ultraviolet radiation.

THE ANCIENT MARTIAN ENVIRONMENT

The surface environment of Mars may not always have been so hostile to life. Early in the planet's history, the average temperature almost certainly was warmer and the atmosphere more dense, and liquid water may have existed at the surface. Evidence for the presence of surface water on early Mars comes from interpretation of the geomorphology of the planet's surface. A substantial fraction of the surface of Mars is older than about 3.5 billion years, based on the number of impact craters, which provide a window into the planet's early history.

Two aspects of these older surfaces suggest that the climate prior to about 3.5 billion years ago was different from the present climate (Squyres and Kasting, 1994). First, impact craters smaller than about 15 kilometers in diameter have been obliterated on these older surfaces, and impact craters larger than this have undergone substantial degradation, whereas younger impact craters have not been altered significantly. This suggests that erosion rates were up to 1,000 times larger early in martian history. The style of erosion that is seen on some of the remaining larger impact craters is indicative of water runoff, and water erosion is considered to be responsible for removing the smaller craters. Second, many of the same older surfaces contain networks of valleys that form dendritic patterns similar to terrestrial water-carved stream channels. There is continuing debate as to exactly how these valleys were formed—the process may have involved runoff of precipitation, seepage of subsurface water in a process termed "sapping," or erosion by water-rich debris flows. Independent of the exact process, their formation must have involved the presence of liquid water at or very near the surface during these earlier epochs (Carr, 1996).

Thus, geological evidence suggests that the martian climate prior to about 3.5 billion years ago was somehow warmer than the present climate and that liquid water flowed on the surface in a way that is not observed today. Unfortunately, the observations do not allow a unique determination of what the temperature, atmospheric pressure, or partitioning of liquid water between the subsurface, surface, and atmosphere were at that time. Evidence from measurements of martian stable isotopes suggests that a large fraction of the volatiles from early Mars may have been lost to space, causing the surface environment to become cooler and drier and to evolve into the state observed today (Jakosky et al., 1994).

COULD LIFE HAVE ARISEN ON MARS?

Life on Earth appeared sometime prior to 3.5 billion years ago, although the details of its origin are unknown (e.g., Chyba and McDonald, 1995). The origin of life is believed to require a source of organic molecules, a source of energy that can drive disequilibrium processes, and access to the biogenic elements (such as carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus) (Chang, 1988). The source of organic molecules could be external—for example, organic molecules formed in interplanetary space and supplied to Earth along with meteoritic dust and debris that accreted onto Earth, or terrestrial, formed by chemical reactions in Earth's environment. Transient evaporating ponds, hydrothermal vents where water circulates beneath the surface near volcanic intrusions, and the surfaces of clay minerals that could provide stability and order to long chains of molecules have all been postulated as candidate environments where prebiotic chemistry may have undergone a transition leading to self-replicating entities.

Significantly, molecular phylogeny techniques that allow determination of the genetic distances between modern-day terrestrial species (Woese, 1987) suggest that their most recent common ancestor may have been hyperthermophilic, existing in water heated by near-surface volcanic magma. This indicates either that life first arose in a hydrothermal (hot-spring-like) environment or that it passed through some hydrothermal bottleneck event, such as heating of the early oceans by an energetic asteroid impact, during which nonhyperthermophilic organisms were exterminated.

Hot-spring environments may have been widespread on early Mars (Brakenridge et al., 1985). Hot springs or hydrothermal systems require water in the crust and substantial sources of heat. Local heating of the crust can result from meteorite impacts. Such impacts were a common occurrence during the tail end of the heavy bombardment, as recorded in the impact craters on the oldest surfaces; thus local thermal anomalies that could have driven hydrothermal systems were probably common at the time. Isotopic evidence from martian meteorites indicates that the planet melted globally and differentiated shortly after accretion. The hot initial conditions imply extensive early volcanism. The rate of volcanic activity probably declined with time, but numerous volcanic landforms indicate that Mars has remained volcanically active throughout its history. Clearly, there has been sufficient heat to drive hydrothermal circulation throughout the history of the planet, although such activity was more common early in its history.

Geological evidence also suggests that abundant water has been present in the crust (Carr, 1996). The evidence is derived from the form of the valley networks that involved liquid water, as discussed above; catastrophic flood channels that indicate the presence of water reservoirs in the crust; morphologies such as rampart crater ejecta and lobate debris aprons that might be indicative of near-surface ice; and, of course, the polar caps, which contain substantial quantities of water. Given the extensive evidence for both heat sources and accessible water, it is likely that hydrothermal systems have been present throughout martian history.

The climate on early Mars may have been similar to the climate on Earth at that time. Although martian erosion rates undoubtedly were substantially lower than terrestrial erosion rates, suggesting less widespread water, liquid water certainly was present on both planets. Both planets probably had a mildly reducing atmosphere, containing substantial quantities of carbon dioxide. Given that life arose on Earth, it seems possible and even plausible that life could have arisen on Mars under similar conditions and at roughly the same time. If such were the case, a significant community of microorganisms may have existed on early Mars (McKay et al., 1992a,b; Boston et al., 1992).

Interestingly, an alternative source for life on Mars may have been Earth itself. Asteroid impacts are capable of ejecting rocky material from planets into space (see Chapter 3). Once in space, close encounters with their planet of origin would alter the orbits of such material. The orbits of material ejected from Mars could evolve to the point that they would cross the orbit of Earth; similarly, ejecta from Earth could evolve to the point that their orbits would cross the orbit of Mars (Melosh, 1988; Gladman et al., 1996). At that point, collisions could occur, providing a mechanism for transferring mass from one planet to the other. Meteorites have been discovered on Earth that are identified as having come from Mars, indicating that this process actually does occur. A martian origin for these meteorites is indicated by their young age, by the presence of oxygen isotopes that rule out an origin on Earth or the moon, and by gases trapped within them that are identical in composition to the martian atmosphere and distinct from any other known source of gas in the solar system (Bogard and Johnson, 1993; McSween, 1994). Some of the material ejected by an impact is not heated or shocked substantially, and bacteria or bacterial spores may be able to survive the ejection event. If organisms or spores could survive within a rock during interplanetary transit and find a satisfactory environment on a new planet, they could possibly survive and multiply. This would allow living organisms on one planet to be transferred to another. Indeed, one can ask the following questions: On which planet did life originate? Could life have originated on Mars and been transferred to Earth or vice versa?

IF LIFE DID ARISE, COULD IT SURVIVE UP TO THE PRESENT TIME?

If life forms ever existed on Mars, either by having been formed in an independent origin or by having been transferred there from Earth, it is possible that they have continued to exist up to the present time. Such life forms could survive in occasional localized ecological niches. Such niches could be liquid water or hot springs associated with extrusive and intrusive volcanism or liquid water buried deep beneath the surface where it is stable. It is important to note, however, that biological material may not stay confined in such locations; organisms conceivably might produce dormant propagules (spores) that could be dispersed more widely.

Although volcanism has been declining in intensity throughout the latter half of martian history, it has occurred up to recent times and possibly to the present (Greeley and Schneid, 1991). Certainly, volcanism has occurred in the most recent recognizable geological epoch. This epoch, known as the late Amazonian, occupies approximately the last half billion years of martian history. Evidence for recent volcanism also comes from the martian meteorites. Many of these are basaltic rocks formed by volcanism more recently than 200 million years ago, and so it seems unlikely that volcanic activity just recently ceased. The abundance of water in the martian crust suggests that recent surface or near-surface volcanism might involve associated hot springs or near-surface hydrothermal systems where life could thrive. In addition, life could exist deep in the crust, where liquid water could occur. The geothermal temperature gradient is such that Mars is likely to have liquid water near the equator at depths as shallow as only about 2 kilometers (Carr, 1996). The presence of water is suggested by large flood channels that appear to have been caused by the occasional sudden release of large quantities of water from deep below the surface. The recent discovery of terrestrial organisms living deep within the Columbia River basalts in the Pacific Northwest (Stevens and McKinley, 1995), and elsewhere on Earth as deep as 3 kilometers below the surface, bolsters the possibility of organisms living under similar conditions on Mars. These organisms survive by metabolizing hydrogen that has been produced by chemical interactions between pore water and the basalt; they are thought to be completely independent of any input of chemical energy from the surface, and to survive completely isolated from it. Presumably, these organisms did not originate in the basalt but migrated there from elsewhere. Similar migration to the deep subsurface could have occurred on Mars as surface temperatures declined from early higher values to their present cold level.

Did results from the Viking mission in the late 1970s not suggest that Mars was probably devoid of life? That was the accepted interpretation at the time, based on the results of three experiments that tested for biological activity and the absence of organic molecules in the surface materials (Klein, 1979). However, this conclusion may be open to some debate based on recent advances in our understanding of biology. The Viking experiments were able to test for only a couple of the possible mechanisms by which putative martian organisms might obtain energy; these involved the utilization of either carbon dioxide or extant organic molecules as a source of carbon in the production of organic molecules. Putative martian biota might employ other mechanisms to obtain energy and might do so under physical conditions quite different from those of the Viking biology experiments. Martian life also might reside in the interior of rocks (which were not sampled by Viking), where liquid water might occur. Finally, if life exists only in isolated oases where liquid water exists, such as recent volcanic vents or fumaroles, the Viking experiments might have been the right ones but carried out at the wrong location.

Furthermore, recent analyses of one of the martian meteorites, ALH84001, suggest that it contains possible indicators of ancient biological activity (McKay et al., 1996). This meteorite crystallized 4.5 billion years ago and contains abundant carbonate veins that appear to have been deposited in water through aqueous or hydrothermal activity. The possible indicators include carbonate mineral zonation and the presence of mineral grains similar to those found in terrestrial mineral deposits of biological origin, the presence of polycyclic aromatic hydrocarbons (PAHs) that may be remnants of decayed organic matter (although PAHs can also be formed by inorganic processes), and the presence of features that some researchers have interpreted as bacteria-like fossil biota. However, despite the occurrence of several intriguing indicators, the biological origin of these features has not yet been demonstrated with a high degree of certainty.

CONCLUSIONS

In summary, the surface of Mars is inhospitable to life as we know it, although there may be localized environments where life could exist. Conditions on Mars may have been conducive to the formation of life, either during an earlier epoch when the climate was likely more clement or in hydrothermal systems and hot springs that may have existed on Mars throughout geological time. Therefore, it is possible that life arose on Mars. It is also possible that living organisms from Earth could have been delivered to Mars by impact transfer, and, if so, such organisms might have chanced upon the occasional oasis in which they could survive and multiply. If life arose on Mars or was delivered to Mars from Earth, it is possible that it has survived in localized environments that may be more hospitable than the general surface. Thus, there are plausible scenarios in which a sample returned from Mars could contain living organisms, either active or dormant.

3

The Significance of Martian Meteorites

If living microorganisms have existed on Mars, it is possible that such organisms could have been intermittently transported to Earth throughout geological time, carried by meteorites of martian origin. To date, 12 meteorites from Mars have been found on Earth. They are believed to have been ejected from Mars into heliocentric orbits by large impacts and subsequently captured by Earth. The evidence for a martian origin is compelling (McSween, 1994), and there is broad consensus in the scientific community that the meteorites indeed came from Mars.

The rate of influx of martian meteorites onto Earth can be estimated only crudely. Roughly 500 meteorites larger than 0.5 kilograms are thought to fall on Earth every year, but only about 4 are actually observed because most fall in the ocean or sparsely populated areas (Mason, 1962; Brown, 1960, 1961). Of 210 meteorites observed to fall between 1815 and 1960 in densely populated areas of Japan, India, Europe, and North America, 3 were from Mars, and so the ratio of martian meteorites to total meteorites is roughly 1:100. This number is very approximate. So far, 6 martian meteorites have been identified among the 8,000 meteorites recovered from Antarctica. However, considerable analysis is required to identify martian origin, and most of these meteorites have undergone only cursory examination. If we accept the 1:100 ratio as being representative, then of the roughly 500 meteorites that fall on Earth every year, perhaps 5 are from Mars. Because meteorites resemble terrestrial rocks, they generally are recovered only when recovery is favored by special circumstances, such as their having been observed to fall or their landing on the Antarctic ice sheet.

A question of major importance with respect to back contamination is whether putative martian organisms could survive ejection from Mars, transit to

Earth, and entry into Earth's atmosphere. The Shergottites[1] show significant shock metamorphism, but the Nakhlites, Chassigny, and ALH84001 show little evidence of shock damage as a result of ejection from Mars (McSween, 1994). Passage through Earth's atmosphere would heat only the outer several millimeters, and survival of organics in ALH84001 and thermally labile minerals in several other meteorites indicates that indeed only minor heating occurred during ejection from Mars and passage through Earth's atmosphere. Transit to Earth may present the greatest hazard to survival. Cosmic-ray exposure ages of the meteorites in current collections indicate transit times of 0.35 million to 16 million years (McSween, 1994). However, theoretical modeling suggests that about 1 percent of any material ejected from Mars should be captured by Earth within 16,000 years and that 0.01 percent would reach Earth within 100 years (Gladman et al., 1996). Thus, survival of organisms in a meteorite, where largely protected from radiation, appears plausible. If microorganisms could be shown to survive conditions of ejection and subsequent entry and impact, there would be little reason to doubt that natural interplanetary transfer of biota is possible.

Transport of terrestrial material from Earth to Mars, although considerably less probable than from Mars to Earth, also should have occurred throughout the history of the two planets. It is possible that viable terrestrial organisms have been delivered to Mars and that, if life ever started on Mars, viable martian organisms may have been delivered to Earth. Such exchanges would have been particularly common early in the history of the solar system when impact rates were much higher.

During the present epoch, no effects have been discerned as a consequence of the frequent delivery to Earth of essentially unaltered martian rocks both from the martian surface and from well below. It cannot be inferred, however, that there have been no effects.

[1]Shergottites, Nakhlites, and Chassigny are classes of martian meteorites named after the location in which the first representative of the class was discovered. ALH84001 is the name of a particular martian meteorite that does not fit into any of the three aforementioned classes.

4

The Potential for Large-Scale Effects

Contamination of Earth by putative martian microorganisms is unlikely to pose a risk of significant ecological impact or other significant harmful effects. The risk is not zero, however.

As discussed in Chapter 2, the possibility that a living organism, either active or dormant, could be included in a sample returned from Mars cannot be ruled out altogether, although the potential for such an occurrence is judged to be low. The risk of pathogenesis, or of adverse environmental effects, resulting from inadvertent contamination of Earth with hypothetical martian microbes is lower still, although it is not zero. Accordingly, it is reasonable for NASA to adopt a prudent approach to sample return, erring on the side of caution and safety.

Contrary to popular perception, the capacity for inducing disease (pathogenesis) is rare among Earth's microbes. Despite the stunning diversity of Earth's microbial communities and their wide-ranging physiological and metabolic properties, only a tiny fraction of chemoorganoheterotrophic (see Box 1 for explanation of terms) microbes produce adverse effects in host organisms. Pathogenesis is even rarer among phototrophs, lithotrophs, and autotrophs. In contrast, innocuous and mutually beneficial associations between microbes and other terrestrial organisms are so common that strenuous technical efforts are required to prevent the inhabitation of plants and animals by benign microorganisms. In general, microorganisms introduced into natural ecosystems are not known to significantly alter their new environments.

While the risk of large-scale effects is low, the consequences are potentially serious. Therefore, unless and until sufficient knowledge of Mars and its environment is available such that assessment of the risk of pathogenesis, environmental disruption, or other harmful effects resulting from the inadvertent contamination of Earth with hypothetical martian microbes can be effectively reduced to zero, due caution and care should be exercised in handling materials returned to Earth from Mars.

Recommendation. Samples returned from Mars by spacecraft should be contained[1] and treated as though potentially hazardous until proven otherwise. No uncontained martian materials, including spacecraft surfaces that have been exposed to the martian environment, should be returned to Earth unless sterilized.

Recommendation. If sample containment cannot be verified en route to Earth, the sample, and any spacecraft components that may have been exposed to the sample, should either be sterilized in space or not returned to Earth.

Recommendation. Integrity of containment should be maintained through reentry of the spacecraft and transfer of the sample to an appropriate receiving facility.

Recommendation. Controlled distribution of unsterilized materials returned from Mars should occur only if rigorous analyses determine that the materials do not contain a biological hazard. If any portion of the sample is removed from containment prior to completion of these analyses, it should first be sterilized.

Samples returned from the martian surface, unless returned from sites specifically targeted as possible oases, are unlikely to harbor extant life as we know it, and there may be some pressure to reduce planetary protection requirements on subsequent sample-return missions if prior samples are found to be sterile. Presumably, however, subsequent missions will be directed toward locations on Mars where extant life is more plausible based on data acquired from an integrated exploration program, including prior sample-return missions. Thus, planetary protection measures may become more rather than less critical as the exploration program evolves. At some point it may be reasonable to relax the requirements, but this should only be done after careful scientific review by an independent body.

Recommendation. The planetary protection measures adopted for the first Mars sample-return missions should not be relaxed for subsequent missions without thorough scientific review and concurrence by an appropriate independent body.

THE POTENTIAL FOR PATHOGENIC EFFECTS

Pathogenesis can be divided into two fundamental types: toxic and infectious. Generally, toxic effects of microorganisms are attributable to cell components or metabolic products that incidentally damage other organisms. Certain bacteria, algae, and fungi, as well as some animals and many plants, produce substances that interact with the nervous or immune systems of animals. This

[1]The words "contained" and "containment" are used herein to indicate physical and biological isolation.

Box 1
Classification Nomenclature

A nomenclature based on the classification of microorganisms by nutritional requirements is designed to reflect three properties: the principal process for generating metabolic energy, the source of electrons for energy-converting reactions, and the form of environmental carbon assimilated for growth. The processes for generating metabolic energy can be divided into two classes: chemical oxidation and light absorption, designated by the prefixes chemo- and photo-, respectively. Likewise, the sources of electrons for biological energy-converting reactions can be divided into two broad classes: inorganic and organic, designated by the prefixes litho- and organo-, respectively. Finally, the sources of carbon assimilated for growth can be classified as either inorganic or organic, designated by the prefixes auto- and hetero-, respectively. A photoorganoheterotroph, for example, uses light energy to excite electrons extracted from organic compounds to support the assimilation and transformation of carbon from organic compounds. If humans were microbes, they would be classified as chemoorganoheterotrophs.

interaction is usually irrelevant to the existence of the producing organism but may be damaging or even fatal to the infected organism.

Infectious agents, which may be actively or opportunistically invasive, must multiply in or on the host in order to cause damage. The capacity of a microbe to infect a host requires an intimate interaction between the pathogen and the host and often depends on highly specific interactions between cell surfaces of the host and pathogen. Above all, infectious agents must overcome the defenses that have evolved in most potential hosts as a consequence of persistent, unremitting challenges by potential pathogens on Earth. Living organisms defend themselves mechanically and chemically in diverse ways against agents that are themselves constantly changing.

The chances that invasive properties would have evolved in putative martian microbes in the absence of evolutionary selection pressure for such properties is vanishingly small. Subcellular disease agents, such as viruses and prions, are biologically part of their host organisms, and an extraterrestrial source of such agents is extremely unlikely.

THE POTENTIAL FOR ECOLOGICAL EFFECTS

Although hypothetical extraterrestrial biota could have properties different from those of Earth biota, it must be assumed that the chemical reactions governing their metabolism would be largely the same. Putative martian microorganisms would likely be functionally similar to some of Earth's soil bacteria, but because the range of habitats available on Mars is much narrower than that on

Earth, the diversity of putative martian organisms would be correspondingly smaller.

If hypothetical martian organisms are indeed functionally similar to microorganisms on Earth, there would be little threat of widespread ecological disruption resulting from their inadvertent introduction into the biosphere. Such organisms would meet stiff competition for resources in habitable sites, where, if there is water that is at least occasionally liquid, there will be a community of microorganisms that is well adapted to existence at that site and exploits its resources to the limits of their availability.

Extraterrestrial microorganisms would be unlikely to utilize nutrients that Earth organisms do not already consume efficiently. Few compounds containing available potential energy are known that cannot be consumed by terrestrial microorganisms. A great deal of study has been devoted to biodegradation of diverse substances. In most cases, microorganisms have been found that consume energy-yielding compounds. When utilization is limited, it is generally limited by physical constraints such as lack of critical nutrients or physical inaccessibility, rather than by microbial potential. Extraterrestrial organisms would be limited by these same physical constraints.

It is unlikely that putative martian organisms would be capable of out-competing Earth organisms for nutrients. Earth's microorganisms are optimally adapted to their environments as a result of millions of years of intense competition. Laboratory microbes that have been bred and engineered to utilize (and thereby biodegrade) particular substances at an accelerated rate usually fail in the field because they cannot compete with the well-adapted microorganisms that already exist there (Fry and Day, 1992).

CONCLUSIONS

The possibility of life on Mars cannot be excluded on the basis of our current understanding of the martian environment (see Chapter 2). Nevertheless, the potential for including a living entity in a sample returned from Mars is judged to be low, especially if the sample is returned from a site that has not been specifically targeted as a possible oasis. The potential for returning an organism that could grow and multiply in the terrestrial environment is lower still. If an organism were returned that could survive on Earth, the potential for large-scale ecological or pathogenic effects still would be low. Any organism that could survive in Earth's environment would meet intense competition from well-adapted terrestrial organisms that occupy their habitats to the limits of available resources. It is especially unlikely that putative martian organisms could be agents of infectious disease. Such a capability requires specific adaptations, for which there would be no selection pressure on Mars, to overcome the elaborate defenses against invasion possessed by terrestrial organisms.

There are large uncertainties associated with these assessments, however, and the risk of potentially harmful effects is not zero.

5

Scientific Investigations That Could Reduce Uncertainty

Uncertainties with regard to the possibility of extant martian life can be reduced through a program of research and exploration that might include data acquisition from orbital platforms, robotic exploration of the surface of Mars, the study of martian meteorites, the study of Mars-like or other extreme environments on Earth, and the study of returned samples. However, each returned sample should be assumed to contain viable exogenous biological entities until proven otherwise.

A number of avenues of scientific research could provide a context for understanding the uncertainty regarding the possibility of extant martian life. Research questions that could reduce uncertainties regarding the extent to which Mars is a possible abode for life include the following:

- *Are there locations on Mars where life could exist?*—There are theoretical reasons to believe that the range of environments on Mars overlaps the range of habitats that living organisms can exploit. Direct evidence is not available, however. The search for potential habitats is closely related to other research goals, which may not necessarily be specifically directed to the search for life, such as the search for evidence of water, active volcanism, or the presence of nonequilibrium gases.
- *Are there environments on Mars that are inherently sterile?*—It is conceivable that some environments on Mars are so inimical to life that organisms cannot survive there. If it could be shown that the physical and chemical properties of a particular martian environment preclude the existence of living organisms or dormant propagules (spores, cysts), such evidence could serve as a basis for reevaluating planetary protection criteria for that location.
- *Can meteorites carry living organisms between planets?*—Living organisms might be dispersed between the terrestrial planets in debris launched into space by asteroid impacts (see Chapter 3). Direct evidence for the transfer of living organisms between planets is not currently available. The ecological consequences of such a phenomenon have not been fully explored but conceivably could be of consequence for planetary protection policy.

In addition to increasing our understanding of the limits and potential of life on Earth, other useful avenues of research include the search for, and investigation of, potential habitats for life on Mars and investigation of martian meteorites that have landed on Earth.

THE STUDY OF LIFE ON EARTH

Life on solar system bodies other than Earth, if any, would likely be similar, at some functional level, to microorganisms found on Earth, since the same geochemical constraints on energy transduction will apply. Understanding the limits of microbial life on Earth may yield clues to possible life on Mars. Studies of Earth ecosystems hypothesized to be analogous to putative martian ecosystems, such as the dry valleys of Antarctica or deep subsurface environments, could yield information useful to the search for life in samples returned from Mars.

If there is no feasible photosynthetic zone on Mars, any extant life must obtain energy from inorganic sources. Such sources are known to be utilized by Earth organisms (Jannasch, 1995; Stevens and McKinley, 1995), but the extent and ecology of such systems remain largely unknown. Further research would help determine the limiting factors in such model systems and the extent to which they are relevant to possible environments on Mars.

The martian surface is thought to be extremely oxidizing, extremely desiccated, and bathed in intense ultraviolet radiation, although there may be localized regions where conditions are less hostile to life. It is possible that the regolith, or pulverized rock debris that covers most of the surface, will prove to be uninhabitable by any living organism and inimical to organic carbon. However, highly resistant spores or cysts dispersed by putative organisms occupying more clement environments might possibly survive in the regolith. The study of the ability of terrestrial microorganisms and their resting states (spores, cysts) to withstand extreme conditions may shed light on this possibility.

There have been several proposals that particular assemblages of microorganisms with specific physiological capabilities could survive on Mars (e.g., Freidman and Ocampo-Freidman, 1984; McKay et al., 1992b; Boston et al., 1992; Stevens and McKinley, 1995). These proposals could be evaluated better if they were demonstrated under simulated Mars conditions, as defined by ongoing exploration. This would help determine whether the habitat requirements are met by known martian environments.

It may be possible that Mars harbored life at an earlier time when conditions on its surface were more favorable and that viable remnants are preserved in sedimentary mineral deposits or other precipitates. The ability of such deposits to shield living organisms or their resting states from the extreme conditions on the martian surface would be an appropriate subject for investigation. There have been reports of Earth organisms surviving up to 40 million years while encased in amber (Cano and Borucki, 1995) and up to 100 million years while encased in halite crystals (Norton et al., 1993). Further investigation may increase our understanding of the ability of life to survive in a resting state for extended periods of time under adverse conditions.

The origin and validity of fossil features on Earth reported to be the remains of extremely small bacteria also may be appropriate subjects for additional research. Bacteria are known to cause or facilitate mineral precipitation around themselves in a number of settings, resulting in bacterial pseudomorphs composed of inorganic minerals (Beveridge et al., 1983; Ferris et al., 1994; Southam and Beveridge, 1994; Southam et al., 1995). Several investigators have proposed that certain mineral features found in various settings on Earth may represent fossilized remains of bacteria (Folk, 1993; Sillitoe et al., 1996).

Reliable methods for determining whether such features are truly biogenic would be useful in evaluating samples returned from Mars.

FURTHER EXAMINATION OF MARTIAN METEORITES

Continued and intensified study of martian meteorites could yield valuable data about physical and chemical conditions on Mars and the possibility of extinct or extant life there. Studies of the 12 known martian meteorites have already yielded information about hydrothermal rock alteration and the climatological history of Mars (Gooding, 1992). Some of these meteorites contain fractures filled with secondary minerals that are geologically similar to subsurface formations on Earth that are known to support microbial life (Stevens and McKinley, 1995; Kostelnikova and Pederson, 1996). Some researchers (e.g., McKay et al., 1996) have suggested that one of these meteorites contains evidence of past biological activity on Mars, although this has yet to be determined with certainty. Until samples from Mars are returned to Earth, the martian meteorites afford what is perhaps the best opportunity to explore the potential of Mars as an abode for life.

REMOTE AND IN SITU OBSERVATIONS OF MARS

NASA's *An Exobiological Strategy for Mars Exploration* (NASA, 1995) indicates that any sample-return mission should be an integral part of a comprehensive exploration program and should be preceded by a number of orbital and landed missions, the purpose of which is to conduct a systematic study of the martian environment. The exact nature of the orbital and landed missions that will be sent to Mars has yet to be determined, and the Space Studies Board task group does not have the requisite expertise to make specific recommendations in this area. However, the task group strongly endorses NASA's strategy as an effective means of characterizing the potential of Mars to harbor life. The use of remote sensing and in situ observations to identify and evaluate sites of potential biological significance on Mars prior to any sample-return mission would serve not only to refine our understanding of the potential for extant life on Mars but also to maximize the scientific utility of returned samples.

6

Evaluation and Characterization of Samples Returned from Mars

The initial evaluation of samples returned from Mars will focus on whether they pose any threat to Earth's biosphere. The only potential threat posed by returned samples is the possibility of introducing a replicating biological entity of nonterrestrial origin into the biosphere. Therefore, the initial evaluation of potential hazard should focus exclusively on whether the samples contain any evidence of organisms or biological activity. The scientific and technical knowledge available to address this task has improved enormously since the days of the lunar sample-return missions.

SEARCHING FOR SIGNS OF LIFE

Based on our current understanding of biology, it must be assumed that life elsewhere, if it exists at all, is composed of the same chemical elements and compounds that make up living organisms here on Earth. Extremely sensitive methods of chemical analysis are available, and these techniques will no doubt improve considerably by the time returned samples are ready to be examined. For example, methods for detecting biogenic compounds and resolving isotopic signatures soon may be capable of identifying a single cell in an otherwise sterile matrix of sample material. Specialized staining techniques are available that allow the identification of nucleic acids, proteins, lipids, and other biomolecules. With some additional research specifically directed toward developing improved techniques for detecting life at very low limits, this capability could be greatly extended.

Initial investigations of martian samples will include optical and scanning electron microscopy to search for possible microbial bodies. There are no known living systems that are not associated with structures. Even the simplest organisms require membranes to establish charge separation and to separate cell components from the external environment. The technology for viewing surfaces or preparations and searching for features in the size range[1] of biological entities has undergone rapid development, and, if features are identified that are reminiscent of cells or cell components, the technology soon will be available to determine whether such features are of biological origin.

If a community of only a few organisms occurs in a portion of sample material to be analyzed, the techniques of life detection are expected to be sufficiently advanced by the time a martian sample actually is returned to Earth that there is confidence that those organisms will be detected. The chief difficulty will be preparing a representative portion for analysis. Any returned sample is likely to be heterogeneous, containing rock fragments of various types as well as soil. Great care will be required to select a representative portion that includes all of the potential habitats included in the overall sample. Choosing the portions for detailed analysis will be a critical task for the science team associated with the sample-receiving facility.

AVOIDING FALSE POSITIVES

Although forward contamination of Mars by terrestrial organisms conveyed aboard outbound spacecraft will be stringently avoided, it will remain possible that organisms from Earth could be transported to Mars and, in turn, contaminate the returned sample. It should be possible, however, to distinguish organisms that evolved on Earth from those that evolved on Mars through the use of molecular sequence comparisons. This technique should be effective even if putative martian organisms share a common ancestry with Earth organisms through the exchange of meteoritic debris (see Chapter 3), as long as the organism has had sufficient time on Mars to evolve away from its terrestrial ancestor.

EVALUATING SAMPLE MATERIAL FOR POTENTIAL HAZARDS

It is conceivable that returned samples could contain compounds that would be toxic to the researchers handling the sample material. This is not a planetary protection issue. The amount of material to be returned is quite small, and there is simply no danger to the public posed by a small, well-contained portion of material, even if it does happen to contain toxic compounds. Any potential dan-

[1]Biological features should be greater than 10 nanometers in any dimension; the thinnest membranes are approximately 8 nanometers in width.

ger to the researchers analyzing the samples would be obviated by standard laboratory control procedures.

The only risk posed by a sample returned from Mars is the potential for including a replicating organism that could possibly grow and multiply on Earth. The possibility of such an occurrence is remote (see Chapters 2 and 4), but it is not zero. Therefore, adequate precautions must be taken. In Chapter 4 the task group recommends that martian sample material be contained and treated as though potentially hazardous until proven otherwise.

Evaluation of the sample for potential hazards should focus exclusively, then, on searching for evidence of living organisms, their resting states (e.g., spores or cysts), or their remains in the sample. Attempts to cultivate putative organisms, or to challenge plant and animal species or tissues, are not likely to be productive. Moreover, if viable exogenous biological entities are discovered in the sample material, prudence would indicate that they remain segregated from Earth's biosphere (i.e., they should remain in containment or be made nonviable through sterilization).

In keeping with the task group's recommendation in Chapter 4, if viable biological entities are discovered in sample material returned from Mars, and those entities cannot be accounted for by terrestrial organisms conveyed on the outbound spacecraft, then the sample material should be deemed hazardous and no portion should be removed from containment without first being sterilized.

7

The Sample-Receiving Facility

Given that materials returned to Earth from Mars will be contained and treated as though potentially hazardous until proven otherwise (see recommendations in Chapter 4), a sample-receiving facility will be required to ensure containment while the samples are evaluated.

The Mars sample-receiving facility need not be as elaborate or as expensive as the Lunar Receiving Laboratory constructed during the Apollo program to receive samples returned from the moon. Early sample-return missions to Mars will be robotic rather than crewed, thus obviating the need to place astronauts in quarantine. Furthermore, there likely will be no need to attempt to cultivate putative organisms or challenge plants and animals directly; in fact, most terrestrial soil microorganisms cannot be cultured. Thus, the direct examination methods discussed in the previous chapter constitute both a more effective and more efficient approach to life detection. If tests for potential pathogenesis are deemed necessary, they would be more efficiently conducted by challenging cultured plant and animal tissues rather than plants and animals directly.

There will be a need for an appropriately stringent biological containment capability and for a broadly multidisciplinary science team to carry out the initial evaluation and characterization of samples returned from Mars.

LESSONS LEARNED FROM APOLLO

It was evident from the Apollo experience that the science team, and therefore the Lunar Receiving Laboratory as a whole, would have been more effective if the team members had developed experience working together as a group on common problems prior to the receipt of the lunar samples. During preliminary study of those samples, serious problems were encountered, including repeated compromises of quarantine (Bagby, 1975). Many of these problems could have been prevented had the science team and the receiving laboratory been operational well before receipt of the samples.

To avoid similar problems during the initial investigation of samples returned from Mars, and to provide sufficient time to develop and validate the requisite life detection, containment, and sterilization procedures, the science team and receiving facility should be established as soon as possible once serious planning for a sample-return mission has begun. At a minimum, the facility should be operational at least two years prior to launch.

Recommendation. A research facility for receiving, containing, and processing returned samples should be established as soon as possible once serious planning for a Mars sample-return mission has begun. At a minimum, the facility should be operational at least two years prior to launch. The facility should be staffed by a multidisciplinary team of scientists responsible for the development and validation of procedures for detection, preliminary characterization, and containment of organisms (living, dead, or fossil) in returned samples and for sample sterilization. An advisory panel of scientists should be constituted with oversight responsibilities for the facility.

MARS SAMPLE-RECEIVING, CONTAINMENT, AND RESEARCH FACILITY

To meet its responsibilities, the sample-receiving, containment, and research facility should include an appropriately stringent biological containment capability and be staffed by a broadly multidisciplinary team of scientists with expertise in, for example, effective containment of microbes, analysis and curation of geological and biological samples (Gooding, 1990), microbial paleontology and evolution, field ecology and laboratory culture, cell and molecular biology, organic and light stable isotope geochemistry, petrology, mineralogy, and martian geology.

Although NASA has developed extensive plans for a Mars sample-receiving facility (Townsend, 1990), no facility meeting all the requirements currently exists. No NASA center has the required equipment or experience in high-level biological containment. Other governmental organizations, such as the U.S. Army Medical Research Institute of Infectious Diseases and the Centers for Disease Control and Prevention, have expertise in biological containment but may lack expertise in the biology of nonpathogenic microbes, microbial paleontology, and the relevant aspects of geology and geochemistry. The staff of the NASA Ames Research Center (ARC) has some of the required expertise in biology, and the staff of the NASA Johnson Space Center (JSC) has some of the required expertise in geochemistry and sample curation, but neither center has the full complement of expertise required to operate a sample-receiving, containment, and research facility.

Establishment of a multidisciplinary sample-receiving, containment, and research facility could be accomplished in three different ways:

1. Organization of a dispersed center consisting of government and university scientists associated with a sample-receiving facility but who would remain at their home institutions during the research and development phase prior to the return of samples.
2. Creation of enhanced capability at an existing NASA center by combining relevant personnel from ARC and JSC and adding capability and expertise in high-level biological containment.
3. Creation of a new facility, staffed chiefly by new personnel and augmented by selected NASA scientists.

The various investigative techniques and strategies required to adequately characterize and preserve samples returned from Mars interrelate in such a complex way that it will be essential for the multidisciplinary science team to form a consensus on goals and approaches prior to receipt of any sample material. This will occur only if the investigators have sufficient experience working together as a team investigating sample analogs such as martian meteorites and appropriate terrestrial samples. A dispersed center would not naturally facilitate evolution of the team approach that will be so critical to successful operation of the sample-receiving and research facility. If the dispersed-center option is chosen, strenuous effort will be required on the part of NASA management to integrate the efforts of the individual investigators and foster a team approach during the research and development phase prior to actual sample return.

The effectiveness and efficiency of the facility will be enhanced if the same science team that has responsibility for evaluating and characterizing returned samples takes a leading role in developing the techniques and the baseline science required to properly carry out that task. Thus, no matter which option is adopted, the sample-receiving, containment, and research facility should be responsible for advancing the state of the art in life detection, sample sterilization and containment, and the ecological study of extreme environments on Earth that may be similar to possible Martian environments.

The endeavor will be successful only if excellent scientists are attracted to participate. To accomplish this, it would be desirable for the sample-receiving and research facility to focus on Mars-relevant, rather than Mars-only, scientific questions. For example, research could focus on the study of the limits of life in extreme environments—the discovery and characterization of microorganisms inhabiting Mars-like environments on Earth or other extreme terrestrial environments. In addition to being directly applicable to the investigation of martian samples, the life detection techniques thus developed might serve as the basis for improved technology for the robotic exploration of planetary surfaces. Samples returned from Mars would constitute an especially interesting specimen in an ongoing series of specimens analyzed by the facility, and the research carried out there would produce significant scientific results regardless of whether the martian samples contained evidence of past or present life.

8

Program Oversight

In the decades since the lunar sample-return missions, changes have occurred in the perception of risk associated with large-scale scientific endeavors (NRC, 1996, 1989) and in the manner in which programmatic decisions are made for such activities. New laws, more intense government oversight, and increased public involvement in the decision-making process will require that legal, regulatory, and societal issues be addressed early in the planning of any Mars sample-return mission (Race, 1996). The proper design and implementation of planetary protection measures will ultimately be critical to overall mission success.

LESSONS LEARNED FROM APOLLO

During the early years of the Apollo program, while lunar sample-return missions were still in the initial planning phase, it was recognized that planetary protection, particularly protection against back contamination of Earth by hypothetical lunar organisms, was a critical issue that had to be addressed before sample-return missions could go forward. At that time the Interagency Committee on Back Contamination (ICBC) was established to preserve public health and protect agricultural and other resources against the possibility of contamination by hypothetical lunar organisms conveyed in returned sample material or other material exposed to the lunar surface (including astronauts) and to preserve the biological and chemical integrity of lunar samples and scientific experiments with minimal compromise to the operating aspects of the program. The ICBC played a crucial role during both the planning and implementation phases of the first lunar sample-return program, overseeing the broad and diverse issues related to planetary protection.

Retrospective analyses of the Apollo program have identified numerous shortcomings in areas related to planetary protection and quarantine activities despite the helpful advice and guidance of the ICBC. In addition to the scientific and technical problems encountered, organizational and managerial shortcomings compromised the effectiveness of planetary protection measures during the lunar sample-return program. In particular, planetary protection measures were repeatedly overridden by program managers in order to keep the mission on schedule and to maximize the safety and comfort of the crew (Mahoney, 1976).

MARS SAMPLE-RETURN PROGRAM

A Mars sample-return program will differ from the lunar program in a number of key respects. Geopolitical considerations are not likely to figure as prominently in a Mars exploration program as they did in the lunar exploration program, and a Mars sample-return mission will be robotic, not crewed. Most importantly, the consensus among the scientific community at the time of Apollo was that the lunar surface was almost certainly sterile—the same cannot be said of Mars (see Chapter 2). Thus, from a scientific viewpoint, planetary protection is more critical with respect to a Mars mission than it was with the lunar missions, and, from an operational viewpoint, it should be more easily implemented.

For Mars sample-return missions it will be necessary for NASA to interact in a timely manner with appropriate governmental and scientific bodies to coordinate regulatory responsibilities and seek advice regarding planetary protection measures. To formally ensure that such coordinated oversight and advice are obtained, an advisory body similar to the ICBC would be helpful in a broad range of areas, such as clarification of legal issues; coordination of regulatory responsibilities; oversight of the planning and development of a suitable sample-receiving facility; and oversight of recovery, transportation, and quarantine of the sample material, including review and approval of protocols and analyses used to determine whether samples are in any way hazardous. Considering the breadth and complexity of these tasks, it would be desirable to establish this coordinating group as early as possible in mission planning. Planetary protection measures will be most effective and least costly if they are designed into the mission from its inception, rather than treated as an add-on later.

Recommendation. A panel of experts, including representatives of relevant governmental and scientific bodies, should be established as soon as possible once serious planning for a Mars sample-return mission has begun, to coordinate regulatory responsibilities and to advise NASA on the implementation of planetary protection measures for sample-return missions. The panel should be in place at least one year prior to the establishment of the sample-receiving facility (at least three years prior to launch).

The best-laid plans are only as effective as their implementation. It will be necessary to verify that all planetary protection measures are properly carried out throughout the mission, including curation and possible distribution of sample material. Formal administrative oversight is required to avoid the lapses in quarantine and handling that occurred during lunar sample-return missions (Bagby, 1975). Such administrative oversight should be sufficiently removed from mission efforts to maintain an independent perspective and avoid conflicts of interest. NASA should ensure that planetary protection oversight is incorporated into mission planning as early as possible and that it includes identification and conduct of the research and technology development required to properly implement planetary protection measures. Clear lines of authority and accountability should be established within NASA to ensure proper implementation of planetary protection measures.

Recommendation. An administrative structure should be established within NASA to verify and certify adherence to planetary protection requirements at each critical stage of a sample-return mission, including launch, reentry, and sample distribution.

Since the return of lunar samples, significant changes have occurred in the public decision-making realm. New laws, most notably the National Environmental Policy Act, and more open review processes allow for citizen involvement in nearly all aspects of governmental decision making. Technical and scientific decisions about mission hardware and operations, while still made by groups of experts, are now scrutinized by other governmental bodies, the general public, advocacy groups, and the media. The array of environmental, health, and safety laws enacted during the past several decades provides ample opportunity for public involvement, including legal challenges, in many parts of the decision-making process that were previously conducted in private.

In light of the public's past response to other controversies involving science and technology issues, it is possible that environmental and quality-of-life issues will be raised in the context of a Mars sample-return mission. If so, it is possible that the adequacy of planned planetary protection measures will be questioned in depth. The public will need accurate and timely information in order to be appropriately informed about planning and implementation of planetary protection measures during sample-return missions. It is essential that NASA acknowledge the public's legitimate interest in and concern regarding planetary protection from the outset, keeping it fully informed and involved throughout the decision-making process and subsequent implementation.

Recommendation. Throughout any sample-return program, the public should be openly informed of plans, activities, results, and associated issues.

9

Technology Issues

As stated in Chapter 8, the proper design and implementation of planetary protection measures will ultimately be critical to the overall success of martian sample-return missions. Mission success can be most effectively promoted by integrating planetary protection measures into the engineering and design of a sample-return mission as early as possible in the planning phases. Implementing these measures, while preserving the scientific utility of the returned samples and containing overall mission costs, will pose a number of technical challenges. Research and development will be required to advance the available technologies for sample containment, sample sterilization methods that preserve geochemical and other data, in-flight verification of containment, and in-flight sterilization. Sterilization may be a particularly difficult issue. NASA will need to undertake research aimed at the definition and implementation of appropriate sterilization procedures for all phases of a Mars sample-return mission, up to and including the controlled distribution of returned material.

AVOIDING CONTAMINATION OF RETURNED SAMPLES WITH ORGANISMS OR ORGANIC MATERIAL OF TERRESTRIAL ORIGIN

It will be important to stringently avoid the possibility that terrestrial organisms, their remains, or organic matter in general could inadvertently be incorporated into sample material returned from Mars. Contamination with terrestrial material would compromise the integrity of the sample by adding confusing back-ground to potential discoveries related to extinct or extant life on Mars. DNA and proteins of terrestrial origin could likely be unambiguously identified, but other organic material might not be so easily distinguished. The search for candidate martian organic biomarkers would be confounded by the presence of terrestrial material. Because the detection of life or evidence of prebiotic chemistry is a key objective of Mars exploration, considerable effort to avoid such contamination is justified.

Because the martian surface is so hostile to terrestrial life, forward contamination protection protocols specify a low bioburden rather than strict sterility. The measures required to avoid terrestrial contamination of returned sample material exceed those required to avoid forward contamination of Mars. Precautionary measures could include technologies used during the Viking missions, such as stringent cleaning with disinfectants and solvents, encapsulation of critical items with covers that can be removed on Mars, and general protection of sample pathways to isolate sample material from potentially contaminated surfaces.

The 1992 Space Studies Board report *Biological Contamination of Mars: Issues and Recommendations* (SSB, 1992) states that "[l]anders . . . for . . . investigation of extant martian life should be subject to at least Viking-level sterilization procedures. Specific methods for sterilization are to be determined" (p. 47). The intent of this statement was to cite the Viking mission as an example of the successful application of techniques of bioburden reduction. It should not be interpreted as requiring the same whole-vehicle heat sterilization protocol for any lander carrying a life detection experiment. Indeed, other techniques may be both more effective and less costly.

IN-FLIGHT STERILIZATION

The capacity for in-flight sterilization may be required for two reasons: (1) to decontaminate exterior portions of the canister, spacecraft, or other hardware and/or (2) to provide contingency sterilization in the event that sample containment cannot be verified. Candidate sterilization technologies include the use of heat, radiation, or chemical treatment.

Heat sterilization has been the most widely investigated technique (Hochstein et al., 1974), and various time and temperature protocols have been suggested, ranging from 24 hours at 150°C to 1 second at 500°C. Ionizing radiation may afford a less destructive route to sterilization, but implementation could be problematic. Chemical treatments that would ensure the destruction of unknown organisms would likely alter the sample material in ways that would reduce its value for subsequent scientific analysis. These candidate technologies will require further testing and development before they are ready for deployment on a sample-return mission.

SAMPLE HANDLING AND PRESERVATION

It will be necessary to monitor and record the environment to which the sample material has been exposed from the time of acquisition until it is delivered to the ground-based receiving facility. Parameters to be recorded may include temperature, gas environment (pressure and composition), radiation exposure, exposure to magnetic fields, and exposure to shock and acceleration. Scientific considerations may dictate that some of the environmental parameters be controlled during the return flight and reentry. For example, it may be desirable to maintain the sample under ambient martian conditions (cold, dry) at all times. If in-flight sterilization of the returned sample becomes necessary and if heat is chosen as the means of effecting sterilization, it will be desirable to trap and contain the evolved gas products for subsequent analysis.

ENSURING SAMPLE CONTAINMENT

Canisters for returned samples must provide a physical barrier that prevents expulsion or migration of materials of martian origin, or materials exposed to the martian environment, outside of sealing points. This does not necessarily require that canisters be hermetically sealed (gas tight), as long as adequate filtration is provided to prevent transfer of biological entities.

As recommended in Chapter 4, specific measures should be taken to monitor the integrity of sample containment during all phases of a sample-return mission. If containment integrity cannot be verified by remote monitoring during the transit back to Earth, the sample, and any spacecraft components potentially exposed to it, should either be sterilized or not returned to Earth. One means of ensuring maximum safety would be to target the return vehicle away from Earth until, upon near approach to Earth, containment is verified, at which time the required trajectory corrections can be implemented.

Ensuring containment through reentry, descent, and landing will be technically challenging because of the potentially large accelerations and short reaction times that characterize this phase of a mission. All credible failure modes should be examined. For example, the possibility of parachute deployment failure should be accounted for in designing a rugged sample canister. All prudent precautions should be taken to maximize the likelihood of a mild entry event. Such precautions include improved targeting accuracy, tracking aids, and midair retrieval to avoid touchdown impact.

AVOIDING RETURN OF UNCONTAINED MARTIAN MATERIAL

To date, two different methods have been proposed to avoid the return of unsterilized material of extraterrestrial origin that is not strictly contained. One approach involves aseptic transfer of the sample canister through a biobarrier to a receiving spacecraft that returns the sample to Earth. A possible variant of this approach, which avoids hand-off to a second craft, is to pass the sample canister through a biobarrier that fully encloses the Earth reentry vehicle on Mars. Once in space, the biobarrier would be opened like a cocoon to release the Earth reentry vehicle. Technical challenges include the selection of biobarrier materials, designing practical pass-through and sealing mechanisms, and validating the method.

In an alternative approach, all spacecraft surfaces that could be exposed to the martian surface would be coated with a pyrotechnic material that would be ignited in space during the return trip to Earth in order to heat the surfaces and sterilize any attached martian material. As with any method, extensive validation and testing would be required. Such testing would include analysis of the efficacy of heating across a steep gradient and avoidance of ablation or partial detachment of surface material that could defeat sterilization.

It must be assumed that putative martian organisms will be resistant to ultraviolet radiation and able to tolerate high vacuum. Possible mechanisms of biotic transfer within and on the return spacecraft must be considered. Such mechanisms include vibrations and shocks and micrometeorite erosion of surfaces, including a possibly dusty near-Mars environment owing to the proximity of two moons, Phobos and Deimos.

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Appendix

Letter of Request

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

OCT 20 1995

Reply to Attn of: SLC

Dr. Claude R. Canizares
Space Studies Board
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Dr. Canizares:

As stated in NASA Management Instructions 8020.7, the Space Studies Board (SSB) has been the primary group advising NASA on its efforts in planetary protection, which seek to preserve planetary conditions for future biological and organic constituent exploration and to protect Earth and its biosphere from potential extraterrestrial sources of contamination. As envisioned in NASA planetary protection policy, continued advice on planetary protection from the Space Studies Board is needed to ensure that our policy in this area remains robust.

In 1992, the Space Studies Board produced its report "Biological Contamination of Mars: Issues and Recommendations" which provided the basis for a modification of the planetary protection requirements for Mars lander missions. That study was conducted in a planning environment which was more expansive than that of today, but there are several key issues that NASA would like to have the Board study that remain on our planning horizon. In particular, with the onset of the Mars Surveyor series of missions, and with several other planned missions to other solar system objects that intend to return samples to Earth, the issues involved with the potential for back contamination are in need of further study.

At this time, we feel that it would be prudent to initiate a study that would examine the following subjects and provide current advice to NASA by addressing:

1) The potential for a living entity to be included in a sample to be returned from another solar system body, in particular Mars;

2) The scientific investigations that should be conducted to reduce the uncertainty in the above assessment;

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3) The potential for large-scale effects on the environment by any returned entity released to the environment,

4) The status of technological measures that could be taken on a mission to prevent the inadvertent release of a returned sample into the Earth's biosphere; and

5) The criteria for intentional sample release, taking note of the anticipated regulatory framework.

Your help in addressing the question of planetary protection for returned sample missions is greatly appreciated. Dr. Michael A. Meyer, Planetary Protection Officer, will be working with you and the SSB staff to finalize a Statement of Task for this study effort. Please contact him (202-358-0307) if you need further information about this request.

Sincerely,

Wesley T. Huntress, Jr.
Associate Administrator for
Space Science

cc:
SL/Dr. Rahe
Dr. M. Meyer
SS/Dr. Bohlin
NRC/Dr. Allen