THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine
Space Studies Board

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February 8, 2006

Dr. John D. Rummel
Planetary Protection Officer
NASA Headquarters
300 E Street SW
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Dear Dr. Rummel:

As originally written in your letter of February 7, 2005, to Space Studies Board (SSB) Chair Lennard Fisk and reiterated at the February 9-11, 2005, meeting of the SSB's Committee on the Origin and Evolution of Life (COEL), you asked for advice on planetary protection concerns related to missions to and from Venus. In particular, you asked that the National Research Council (NRC) address three issues in terms of their implications for planetary protection:

1. Assess the surface and atmospheric environments of Venus with respect to their ability to support Earth-origin microbial contamination, and recommend measures, if any, that should be taken to prevent the forward contamination of Venus by future spacecraft missions;
2. Provide recommendations related to planetary protection issues associated with the return to Earth of samples from Venus; and
3. Identify scientific investigations that may be required to reduce uncertainty in the above assessments.

In response to your request, the Task Group on Planetary Protection Requirements for Venus Missions was formed (the membership of the task group is listed in Attachment 1) and met at the Southwest Research Institute in Boulder, Colorado, on October 3-5, 2005. The task group's deliberations and discussions relating to the conclusions and recommendations contained in this letter report were confined to the Boulder meeting. To set the context for and define the scope of this study, presentations were given and discussions were held at two meetings of COEL earlier in 2005—the February 9-11 and May 31-June 2 meetings at the National Academies' Keck Center in Washington, D.C., and its Jonsson Center in Woods Hole, Massachusetts, respectively. These preliminary presentations and discussions were conducted under the aegis of COEL's standing oversight of NASA's Astrobiology program and in its role as the organizing committee for the SSB's astrobiological activities. And, since all but two members of the task group are also members of COEL, the majority of the authoring group of this letter report participated in all three meetings and heard the following presentations relevant to this study:

- *At the meeting in Washington, D.C.,* you briefed the committee on the topic "Planetary Protection Classification of Venus," and Dirk Schulze-Makuch (Washington State University) spoke on the question "A Case for Life on Venus?"

- *At the meeting in Woods Hole, Massachusetts,* you presented an updated version of "Planetary Protection Classification of Venus," and Linda Amaral Zettler (Marine Biological Laboratory) addressed the topic "Acidophiles in the Rio Tinto." In addition, Martha Gilmore (Wesleyan University) and James W. Head III (Brown University) gave presentations respectively entitled "NASA Planning for Venus Sample-Return Missions" and "Origin and Evolution of Venus's Environment."
- *At the meeting in Boulder, Colorado,* D. Kirk Nordstrom (U.S. Geological Survey) gave a talk titled "Negative pH, Efflorescent Mineralogy and Consequences for Environmental Restoration at Iron Mountain." Mark Bullock (Southwest Research Institute) gave the presentation "Origin and Evolution of Venus's Environment," and task group member David Grinspoon gave the summary presentation entitled "The Astrobiology of Venus." In addition, individual task group members held extensive discussions in open and closed sessions.

The task group consulted related reports issued by the SSB and other NRC committees (e.g., *Recommendations on Quarantine Policy for Mars, Jupiter, Saturn, Uranus, Neptune, and Titan [1978], An Integrated Strategy for the Planetary Sciences: 1995-2010* [1994], *Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies* [1998], *A Science Strategy for the Exploration of Europa* [1999], and *Preventing the Forward Contamination of Europa* [2000][1]).

In its deliberations, the task group examined planetary protection considerations affecting Venus missions. The known aspects of the present-day environment of Venus offer compelling arguments against there being significant dangers of forward or reverse biological contamination, regardless of the unknowns. Full details are contained in the attached "Assessment of Planetary Protection Requirements for Venus Missions."

Because of the extreme temperature at the Venus surface, the fact that concentrated H_2SO_4 is sterilizing for all known Earth organisms, the consideration that the Venus cloud environment is extremely dehydrating and oxidizing, and the realization that any life forms adapted to the Venus clouds would not survive in Earth conditions, **with respect to planetary protection issues, the task group concluded as follows:**

- **No significant risk of forward contamination exists in landing on the surface of Venus;**
- **No significant forward-contamination risk exists regarding the exposure of spacecraft to the clouds in the atmosphere of Venus;**
- **No significant back-contamination risk exists concerning the return of atmospheric samples from the clouds in the atmosphere of Venus; and**
- **No significant risk exists concerning back contamination from Venus surface sample returns.**

Currently, NASA classifies Venus missions under planetary protection Category II, which "includes all types of missions to target those bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration,"[2] rather than under the less

[1] These reports were published by the National Academy Press, Washington, D.C.
[2] This explanation of Category II and of the other categories is given at the web site <planetaryprotection.nasa.gov/pp/about/categories.htm>. Last accessed February 7, 2006. The explanation of these categories is also reprinted in this letter report in Attachment 2, "COSPAR Categories for Planetary Protection."

restrictive Category I assigned by the Committee on Space Research (COSPAR) of the International Council for Science. **The task group recommends that the Category II planetary protection classification of Venus be retained.** Although there are many important scientific investigations to be carried out to improve understanding and knowledge of Venus, **the task group does not recommend any scientific investigations for the specific purpose of reducing uncertainty with respect to planetary protection issues.** The considerations that led to the above conclusions are presented in the attached assessment.

Sincerely,

Jack W. Szostak, *Chair*
Task Group on Planetary Protection
Requirements for Venus Missions

Attachment:
Assessment of Planetary Protection Requirements for Venus Missions

Assessment of Planetary Protection Requirements for Venus Missions

This assessment by the Task Group on Planetary Protection Requirements for Venus Missions (the members of the task group are listed in Attachment 1) was carried out at a meeting held at the Southwest Research Institute in Boulder, Colorado, on October 3-5, 2005. The assessment was conducted at the specific written request of Dr. John D. Rummel, NASA's Planetary Protection Officer, who asked the National Research Council (NRC) to address three issues in terms of their implications for planetary protection:

1. Assess the surface and atmospheric environments of Venus with respect to their ability to support Earth-origin microbial contamination, and recommend measures, if any, that should be taken to prevent the forward contamination of Venus by future spacecraft missions;
2. Provide recommendations related to planetary protection issues associated with the return to Earth of samples from Venus; and
3. Identify scientific investigations that may be required to reduce uncertainty in the above assessments.

VENUS MISSIONS

The United States and the former Soviet Union (with France) have been sending spacecraft to Venus since the beginning of the space age.[1] Missions to land on Venus began with the Soviet Venera 3 atmospheric probe, which lost communications before atmospheric entry in March 1966. Atmospheric probes Venera 4, 5, and 6 also crashed on Venus. On December 15, 1970, Venera 7 made the first successful landing of a spacecraft on another planet and survived for 23 minutes before succumbing to heat and pressure. Venera 8 landed July 22, 1972, and survived for 50 minutes. Between 1975 and 1982, Venera probes 9 through 14 made successful landings.

In 1978, NASA sent two Pioneer spacecraft to Venus. The Pioneer Venus Multiprobe carried one large and three small atmospheric probes. The large probe was released on November 16, 1978, and the three small probes on November 20, 1978. All four probes entered the Venus atmosphere on December 9, 1978, followed by the delivery vehicle. Although not expected to survive the descent through the atmosphere, one probe continued to operate for 45 minutes after reaching the surface. The Pioneer Venus Orbiter was inserted into an elliptical orbit around Venus on December 4, 1978. It carried 17 experiments and operated until the fuel used to maintain its orbit was exhausted and atmospheric entry destroyed the spacecraft in August 1992.

The Soviet Union's Vega 1 and Vega 2 probes encountered Venus on June 11 and June 15, 1985. Landing vehicles carried experiments focusing on cloud aerosol composition and structure. The Vega 1 and 2 spacecraft each deployed a balloon-borne aerostat that floated at about 53 km altitude for 46 and 60 hours, respectively, traveling about one-third of the way around the planet. These probes measured wind speed, temperature, pressure, and cloud density.

Although the most recent spacecraft sent to Venus ceased operating over a decade ago (the last mission was NASA's Magellan radar mapper, which operated until 1994), scientific interest in Venus has not waned. The 2003 NRC report *New Frontiers in the Solar System: An Integrated Exploration*

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[1] For more details of missions to Venus, see, for example, A.A. Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes 1958-2000,* Monographs in Aerospace History 24, National Aeronautics and Space Administration, Washington, D.C., 2002. The brief summary that follows here was adapted from Wikipedia contributors, "Observations and Explorations of Venus," Wikipedia, The Free Encyclopedia, available online at <en.wikipedia.org/w/index.php?title=Observations_and_explorations_of_Venus&oldid=28480484>. Last accessed February 7, 2006.

Strategy[2] recommended the Venus In Situ Explorer as one of eight high-priority planetary exploration projects for the period 2003 to 2013. As a result, NASA is considering possible space missions to Venus, including orbiters, landers, and atmospheric probes. Moreover, several other nations and space agencies are planning to launch missions to Venus in the near future. The European Space Agency's Venus Express spacecraft was successfully launched on November 9, 2005, and the Japan Aerospace Exploration Agency plans to launch a Venus orbiter, Planet-C, in 2008.

SCIENTIFIC CONSIDERATIONS AND PAST NATIONAL RESEARCH COUNCIL REPORTS

Despite Venus's being Earth's near twin in terms of its mass, radius, and other bulk properties, the surface of Venus represents perhaps the most hostile planetary environment ever explored by robotic spacecraft. The average surface temperature of Venus is more than 737 K, hot enough to melt lead. The surface pressure is 92 bar, about equivalent to 1 km deep in Earth's ocean. The surface is desolate, water is absent, and sulfur is abundant. More than 85 percent of the surface is covered by volcanic rock. Venus's atmosphere is more than 96 percent carbon dioxide, with 3 percent nitrogen and traces of other gases. Three distinct cloud layers shroud the entire planet, at altitudes from 45 to 60 km. The clouds occupy the "Earth-like" part of Venus's atmosphere, with pressures ranging from 2 bar to 10 mbar and temperatures ranging from ~240 to 390 K. Water vapor ranges from a few parts per million at the top of the cloud deck to a few tens of parts per million at the base. However, the cloud droplets are formed of extremely concentrated sulfuric acid. A high flux of solar ultraviolet radiation exists throughout the cloud deck.[3]

Although the surface environment of Venus is clearly inimical to terrestrial life, some researchers have argued that conditions in Venus's clouds may be potentially conducive to life.[4] Indeed, some authors have suggested that chemical disequilibrium among trace constituents of Venus's atmosphere is evidence for microbial life in the planet's lower cloud layers.[5,6] In particular, supporters of this conjecture point to the coexistence of chemical species—such as H_2 and O_2 and H_2S and SO_2—not normally found in association and the existence of relatively benign regions in the atmosphere where the temperature is 300 to 350 K, and where pressures of 1 bar and water vapor concentrations as high as several hundred parts per million may exist.[7] Such organisms, presumably, would have evolved when Venus's climate was more like that of Earth and then migrated to the clouds as Venus lost its surface water.

Irrespective of such speculations, the evolution and present states of Venus's atmosphere have a direct bearing on the history and evolution of both biotic and abiotic organic compounds in the solar system. For example, given the similar location in the solar nebula of Mars, Earth, and Venus, these planets are likely to have had roughly similar bulk chemical compositions 4.5 billion years ago and would have been exposed to similar early radiation processes. The extent to which the atmospheres have evolved and diverged since that time yields information on the evolution of Earth's atmosphere and the couplings of atmospheric composition with biology and life. Venus may also provide clues to the composition of past atmospheres on Earth that ultimately would have influenced the distribution of

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[2] National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy,* The National Academies Press, Washington, D.C., 2003.
[3] See, for example, <nssdc.gsfc.nasa.gov/planetary/planets/venuspage.html>. Last accessed February 7, 2006.
[4] D. Schulze-Makuch and L.N. Irwin, *Life in the Universe: Expectations and Constraints*, Springer-Verlag GmbH, Berlin, 2004, pp. 128-132.
[5] D.H. Grinspoon, *Venus Revealed: A New Look Below the Clouds of Our Mysterious Twin Planet*, Perseus Publishing, Cambridge, Mass., 1997.
[6] D. Schulze-Makuch and L.N. Irwin, "Reassessing the Possibility of Life on Venus: Proposal for an Astrobiology Mission," *Astrobiology* 2: 197-202, 2002.
[7] D. Schulze-Makuch, O. Abbas, L.N. Irwin, and D.H. Grinspoon, "Microbial Adaptation Strategies for Life in the Venusian Atmosphere," Abstract 12747, NASA Astrobiology Institute General Meeting, Tempe, Arizona, 2003.

terrestrial organic compounds in the form of, for example, carbon reservoirs in the atmosphere compared with those at the surface, in the interior, and in the oceans.

The Space Studies Board (SSB) has a long track record of assessing the biological potential of Venus and making recommendations concerning appropriate planetary protection guidelines for Venus missions. In 1970, for example, the SSB's predecessor, the Space Science Board, commented as follows:[8]

> A slight possibility exists that terrestrial organisms could grow on airborne particles near to the cloud tops of Venus. The problem was discussed at the 1970 COSPAR [Committee on Space Research of the International Council for Science] meeting, and some interest was expressed in investigations of airborne life. Life on Venus is no more than a remote contingency, but the possibility of contamination by terrestrial organisms must be considered.
>
> The saving feature of all Venus missions is that there is no longer any doubt that a temperature of about 700 K prevails over the entire surface of the planet. There is no possibility that terrestrial organisms can grow at such temperatures, and we are therefore at worst concerned with a short period of transit through the cooler regions of the atmosphere.
>
> According to the COSPAR agreements, the cumulative probability up to 1988 of contaminating the planet must be less than 10^{-3}. With 20 missions, the probability per mission must then be less than 5×10^{-5}. We are satisfied that this constraint is readily met, even if the bus or orbiter should enter the atmosphere. These unshielded vehicles will mostly vaporize in the upper atmosphere, and at most a few charred members may fall rapidly through the temperate region of the cloud tops. For numerical estimates we may start with the figures given in the Planetary Explorer, Phase A Report (Goddard Space Flight Center, October 1969, Section 6 and Appendix C). The number of spores is taken as 10^4. The probability of release in the atmosphere under the above circumstances is estimated to be less than 10^{-3}; we regard the Goddard figure of 0.3 as far too high for atmospheric release, because it was based on a hard-surface impact. The probability of growth was given as 10^{-4}, but this assumes the presence of a stable particle or droplet to grow on. However, droplets are subject to evaporation, while solid particles must be subject to rapid mixing to support them against fallout; they will therefore reach a hot region in a short time. We believe that the probability of growth in the atmosphere should be amended to less than 10^{-6} for a total probability of contamination per impact of less than 10^{-5}.
>
> We therefore see no reason why the bus or orbiter should not be permitted to impact the planet whenever a scientific benefit is to be gained thereby. Low-periapses orbiters should also be open to consideration. Surface-sterilized entry probes, hermetically sealed and with a fully sterilized heat shield, present a far lower probability of contamination than do the bus or orbiter, and risk of contamination from them may be neglected.
>
> We therefore recommend that, with some precautions, spacecraft be allowed to impact the planet when scientific benefit is to be gained thereby.

The most recent NRC study of the planetary protection requirements for Venus missions was issued in 1972.[9] It commented as follows:

> Two values of probability of growth are used for Venus, one for the planet surface, the other for its atmosphere. Prior to the proposed new quarantine policy these values stood at $P_g(\text{surface}) \leq 10^{-6}$ and $P_g(\text{atmosphere}) \leq 10^{-4}$. The proposed new values use $P_g(\text{surface}) = 0$; $P_g(\text{atmosphere}) \leq 10^{-9}$.
>
> There is now general agreement that the surface temperatures of Venus are much too high for any known terrestrial microorganism to survive. Consequently, the proposed value $P_g = 0$ is acceptable.
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> Regarding the atmosphere, there are some uncertainties on the likely presence of sufficient nutrients, a high water activity and the convective rate by which water droplets containing

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[8] National Research Council, *Venus: Strategy for Exploration, Report of a Study by the Space Science Board*, National Academy of Sciences, Washington, D.C., June 1970, pp. 12-13.

[9] National Research Council, Space Science Board ad hoc Committee for Review of Planetary Quarantine Policy, *Report (Final),* February 14, 1972, pp. 3-4.

> microorganisms are transported downwards and pyrolyzed at the higher temperatures. The probability of contaminating the Venus atmosphere was treated in the SSB 1970 summer study;* in that study, a probability of growth for the atmosphere $\leq 10^{-6}$ was recommended and approved by the Space Science Board (a recommendation which superseded the previous value of $P_g \leq 10^{-4}$).
>
> The committee recommends that NASA evaluate their sterilization standards for the Pioneer Venus mission (surface probe) in the light of the P_g(atmosphere) number recommended in the Venus 1970 study report. If further elucidation or interpretation on the application of these numbers is needed, the SSB would be willing to review the matter again.
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> For the Venus/Mercury 1973 flyby mission, the committee recommends a P_g(atmosphere) $\leq 10^{-9}$ (Venus atmosphere).
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> * National Research Council, *Venus: Strategy for Exploration, Report of a Study by the Space Science Board*, National Academy of Sciences, Washington, D.C., June 1970, pp. 12-13.

Since these reports were issued, the approach to planetary protection adopted by the Committee on Space Research (COSPAR) of the International Council for Science—the de facto guardian of the planetary protection provisions mandated by the United Nations' 1967 Outer Space Treaty[10]—has been significantly revised. The quantitative, statistical approach—based in part on the probability of growth (P_g) of terrestrial organisms transferred to an extraterrestrial environment—has been abandoned.[11] In its place is a simpler, more straightforward methodology based on the type of mission (e.g., flyby, orbiter, lander, or sample return) and the degree to which the mission's destination is of interest to the process of chemical or biological evolution (see Attachment 2).

The planetary protection characterization resulting from the two NRC studies conducted in the 1970s was that although Venus was of some interest with respect to issues of chemical and biological evolution—for example, to studies relating to the divergent evolutions of Earth, Mars, and Venus—the chances of contaminating Venus with terrestrial organisms are so slight that no special requirements need be levied on spacecraft missions to that planet. As such, missions to Venus are currently assigned to planetary protection Category II (see Attachment 2 for details).

Much new information about the origin and evolution of Venus's surface and atmospheric environment has, however, been revealed in the past three decades. In the same period, there has been an explosion of new findings concerning the ability of terrestrial microorganisms to survive in extreme conditions. These two strands of new information have been woven together by various authors, who have proposed plausible theories suggesting how life may have arisen on the early Venus, when environmental conditions were much more like those of Earth.[12] Then, as Venus gradually lost its initial inventory of water and its climate became increasingly dominated by a runaway greenhouse effect, microbial life might have been able to adapt to changing conditions and survive to this day in the more

[10] United Nations, *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies,* U.N. Document No. 6347, United Nations, New York, N.Y., January 1967.

[11] The quantitative planetary protection methodology was based on the concept of a probability that a particular mission will contaminate a particular planet. The probability of contamination (P_c) was determined by a formula linking such factors as the measured bioburden on the spacecraft at launch, the likelihood that terrestrial organisms on the spacecraft will survive transit to their planetary destination, the probability that organisms will be released into the planet's environment, and the probability that these organisms will grow and reproduce (P_g). For a recent discussion of this approach, see, for example, Space Studies Board, National Research Council, *Preventing the Forward Contamination of Mars* (Prepublication Text), The National Academies Press, Washington, D.C., 2005, pp. 25-27. For a detailed, quantitative discussion, see, for example, S. Schalkowsky and R.C. Klein, Jr., "Analytical Basis for Planetary Quarantine," pp. 9-26 in L.B. Hall, ed., *Planetary Quarantine: Principles, Methods, and Problems*, Gordon and Breach, New York, N.Y., 1971.

[12] C.S. Cockell, "Life on Venus," *Planetary and Space Science* 47: 1487-1501, 1999.

clement temperature and pressures found in Venus's clouds. Thus, a reexamination of the planetary protection requirements for Venus missions is appropriate at this time.

TOPICS CONSIDERED BY THE TASK GROUP

The task group considered the following topics:

- *Origins of life*—What does our current understanding of the origins and early evolution of life on Earth tell us about the possible origins of life on Venus?
- *Survival of life on Venus*—What can the study of terrestrial extremophiles tell us about the survival of life on Venus, whether it is indigenous or inadvertently transported from Earth?
- *Planetary protection issues*—What can planetary protection studies for other solar system objects tell us about likely issues concerning Venus?
- *Venus's environment*—What can our current understanding of the origin and evolution of Venus tell us about the likely environmental conditions and potential habitable niches on the planet through time?
- *Life in Venus's atmosphere*—What is the environment in Venus's clouds, could life exist there, and what is the likelihood that life exists there?

Origins of Life

It is generally agreed that surface conditions on early Venus were much more Earth-like and far more conducive to life than they are on Venus today. A liquid-water ocean and significant atmosphere are thought to have existed, and many of the processes that have been considered to be relevant to the origin of life on Earth could equally well have occurred on Venus. These include the formation of aqueous solutions of organic compounds that may have originated from meteoritic infall, atmospheric spark-synthesis, the mineral-catalyzed reduction of carbon dioxide or oxidation of methane, and hydrothermal synthesis in submarine vents.

Even if life did independently arise on the surface of Venus, it is very clear that it must have eventually become extinct or migrated to the cloud environment as the runaway greenhouse effect heated up the surface of the planet and evaporated most of the volatiles, except for those that recondensed in the global cloud deck. Any life remaining in the cloud deck would have had to adapt to conditions that do not overlap the range of conditions inhabited by life on Earth. Consequently, considerations of a possible origin of life on Venus are not relevant to considerations of the possibility that life currently exists on the surface of Venus or that living organisms of Earth origin could survive there.

The origin of life within the Venus cloud deck must be considered to be highly improbable. While in principle a living cell could maintain an intracellular environment of neutral pH, higher free-water concentration, and higher ionic strength than that persisting in the sulfuric acid droplet within which it exists, little in the way of protection from these harsh conditions will be available to molecules constituting a newly emerged, minimal self-replicating system. It seems therefore inevitable that cells would be quickly destroyed (or not exist in the first place) rather than continue to replicate.

In principle, life in the Venus ocean could have been transported to the clouds and then persisted there after the point at which life on the surface became impossible and even until the present day. While this hypothesis overcomes the problems inherent in an origin of life within the clouds, it does not overcome the formidable problems that would face an organism living in this hostile environment, which include the following:

- The extremely acidic, dehydrating, and oxidizing environment of the cloud droplet environment, which will lead to the destruction of organic matter;
- The very high energetic cost of recruiting water from concentrated sulfuric acid;
- The high temperatures of the droplets at the cloud base, through which all droplets inevitably cycle;
- The lack of persistence of individual droplets, which have a probable life span of months to, at most, a few years;
- The loss of nonvolatile elements that fall to the surface of Venus; and
- The absence of biogenic elements that do not have volatile forms (e.g., Na, Mg, K, Ca, Mn, Fe, and most other metals). Although these elements could be introduced into the atmosphere by volcanic eruptions and by meteoritic infall, there is no obvious mechanism by which they could become widely distributed among all cloud droplets.

Survival of Earth-Life on Venus

The identification of extremophiles on Earth has expanded knowledge of the physicochemical limits at which life as we know it can exist. Organisms have been shown to grow at temperatures as high as 121°C,[13] in chronic radiation fluxes of 60 gray/hour,[14] in extreme pressures at the bottom of oceans, and in acidities as extreme as pH 0.[15] However, none of these extreme but life-supporting environments approaches the severity of surface and atmospheric conditions present on Venus. In particular, the ambient surface and atmospheric conditions on Venus render all currently known extremophilic phenotypes on Earth irrelevant. Concentrated sulfuric acid is sterilizing for all known organisms. Thus, genetic and other physiologic determinants necessary for life on Earth could not function on Venus, nor would biological determinants that evolved on Venus be expected to function on Earth.

Planetary Protection Issues

Past planetary protection studies have repeatedly addressed the importance of a scientifically sound assessment of what is known and a conservative approach to the unknowns. In the case of Venus, there are many unknown details, particularly about the past, but also about present conditions. In its deliberations, the task group found that the known aspects of the present-day environment offer compelling arguments against there being significant dangers of forward or reverse biological contamination, regardless of the unknowns. Individual points, discussed in more detail elsewhere, merit emphasis. In particular, it is not necessary to know whether life is present in the atmosphere of Venus to conclude that no terrestrial life would be capable of persisting, much less replicating, in any of Venus's extant atmospheric regimes. The dominant factor in this assessment is the concentration of sulfuric acid (and corresponding lack of free water) in cloud droplets in Venus's atmosphere. No region of present atmospheric models is even close to habitable by life carried from Earth.

In terms of chemical contamination of Venus biosignatures by terrestrial material, organic material delivered to the surface of Venus will be rapidly destroyed. Biogenic material deposited in the planet's atmosphere will be either destroyed in situ or eventually (on the timescale of years) carried to

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[13] K. Kashefi and D.R. Lovley, "Extending the Upper Temperature Limit for Life," *Science* 301: 934, 2003.
[14] A. Venkateswaran, S.C. McFarlan, D. Ghosal, K.W. Minton, A. Vasilenko, K. Makarova, L.P. Wackett, and M.J. Daly, "Physiologic Determinants of Radiation Resistance in *Deinococcus radiodurans*," *Applied Environmental Microbiology* 66: 2620-2626, 2000.
[15] K. Edwards, P. Bond, T. Gihring, and J. Banfield, "An Archaeal Iron-Oxidizing Extreme Acidophile Important in Acid Mine Drainage," *Science* 287: 1796-1799, 2000.

lower atmosphere levels, where it will be destroyed. Thus, without biological replication, forward contamination with biomarkers is not a significant issue.

The reverse cannot be demonstrated, but is also hard to escape; life consistent with the environmental conditions in the atmosphere of Venus is not going to find a corresponding niche on Earth. The closest equivalent might be acid mine drainage sites, which can be extremely acidic. However, even these sites are much less acidic than any portion of the Venus atmosphere. In addition, the acid mine drainage sites are generally characterized by extremely high metal-ion concentrations. Venus's clouds, while apparently containing some metallic contaminants, remain poorly characterized in terms of composition and certainly do not possess these high metal-ion concentrations. In terms of metal content, some terrestrial acidic fumaroles or solfataras might be a better match, but none comes close to the acidity of the Venus environment.

Venus's Environment

Our best current understanding of the origin and evolution of Venus suggests that Venus formed with much more water than it has at present, although the water abundance is not well constrained. Venus probably possessed liquid-water oceans during its early evolution, before the main-sequence evolution of the Sun led to warming and the loss of the oceans owing to a moist greenhouse atmosphere, photodissociation of water, and the subsequent thermal and nonthermal escape of hydrogen. The lifetime of Venus's oceans is not known or well constrained but may have been as short as a few hundred million years or as long as several billion years. When the oceans were lost and the surface temperature rose, the potential for life as we know it was completely destroyed on the surface of Venus. The only remaining habitable niche would then have been the clouds. Current understanding of the chemistry and formation of the clouds indicates that the persistence of the global cloud deck depends on continuing surface volcanic activity, as SO_2 is outgassed and oxidized to SO_3, which reacts with water vapor to form sulfuric acid. If volcanic activity ceases, the clouds will be destroyed in roughly 30 million years, as atmospheric SO_2 is destroyed by reaction with surface minerals. It is not clear whether or not the surface has been continuously volcanically active, and therefore it is not clear whether or not the clouds have persisted throughout the history of the planet. There may well have been periods when Venus was entirely cloud free. If this has occurred, any cloud-based microbial ecology would have been permanently extinguished.

Life in Venus's Atmosphere

The clouds occupy the "Earth-like" part of Venus's atmosphere, with pressures ranging from 2 bar to 10 mbar and temperatures ranging from ~240 to 390 K. Water vapor ranges from a few parts per million at the top of the cloud deck to a few tens of parts per million at the base. However, the cloud droplets are formed of extremely concentrated sulfuric acid, with weight percents ranging from 85 percent at the top of the cloud deck (with a slight dip to 82 percent within the upper cloud layer) to 98 percent at the bottom of the lower cloud layer. At these concentrations, the molar ratio of H_2SO_4 to H_2O is ≥ 1, so that all water is protonated (H_3O^+) and tightly bound to the sulfuric acid. Such concentrations dehydrate and oxidize organic compounds.

There is also a high flux of ultraviolet radiation throughout the cloud deck of Venus. The likelihood that life exists in the cloud deck is impossible to assess, given the complete lack of knowledge of the prospects of life in nonterrestrial environments. It has been suggested that some form of life may have evolved that takes advantage of the ultraviolet energy or the chemical disequilibria in the cloud-level gases, which include the coexistence of H_2 and O_2, as well as sulfur in varying oxidation states, including H_2S and SO_2. Such a cloud-based microbial biosphere, if it exists, would need to have evolved mechanisms for surviving in extremely acidic conditions that are unknown in any natural environment on Earth. Given the requirement for adaptation to this extreme environment, such organisms would not have the capacity to survive in the very different conditions found on Earth, as they would have experienced no selective pressure to evolve (or retain) such capacity.

PLANETARY PROTECTION CONSIDERATIONS

In accordance with international treaty obligations, NASA maintains a planetary protection policy to avoid the cross-contamination of Earth and extraterrestrial bodies by spaceflight missions (see Attachment 2). NASA develops implementation regulations based on recommendations from both internal and external advisory groups, but most notably these regulations have been developed on the basis of recommendations provided by the National Research Council.

Historically, constraints on missions—where deemed necessary—have ranged from the cleaning of a spacecraft to reduce its surface bioburden to the heat sterilization of an entire spacecraft prior to launch. In addition, there may be constraints on spacecraft orbits and operating procedures, requirements for the inventory and archiving of samples of the organic constituents of the spacecraft, and the need to document the locations of landing sites and impact points.

NASA has a clear need to obtain external guidance on the planetary protection requirements for Venus missions that is based on a careful assessment of the most recent planetological and biological information. Without such guidance, NASA cannot provide the appropriate guidelines to mission designers, nor can it establish operational procedures for future Venus missions.

NASA states that its planetary protection policy serves the following goals:

- To preserve planetary conditions for future biological- and organic-constituent exploration; and
- To protect Earth and its biosphere from potential extraterrestrial sources of contamination.

Obligations imposed by the United Nations' Outer Space Treaty[16] mandate that spacecraft missions be conducted in such a way as to minimize the inadvertent transfer of living organisms from one planetary body to another.

CONCLUSIONS AND RECOMMENDATIONS

The cloud layers in the atmosphere of Venus provide an environment in which the temperature and pressure are similar to surface conditions on Earth. However, the chemical environment in the clouds, and specifically in the cloud droplets, is extremely hostile. The droplets are composed of concentrated (82 to 98 percent) sulfuric acid formed by condensation from the vapor phase. As a result, free water is not available, and organic compounds would rapidly be destroyed by dehydration and oxidation. Therefore, any terrestrial organisms having survived the trip to Venus on a spacecraft would be quickly destroyed. It is not possible to demonstrate conclusively that a spacecraft returning to Earth after collecting samples of Venus's surface and atmosphere will not come into contact with hypothetical aerial life forms and inadvertently carry them back to Earth; however, this has to be considered an extremely unlikely scenario. At any rate, any life forms that had adapted to living in the extremely acidic environment of Venus's cloud layer would not be able to survive in the environmental conditions found on Earth. No special procedures are warranted beyond those required to maintain the sample integrity necessary for scientific studies of the returned samples.

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[16] United Nations, *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*, U.N. Document No. 6347, United Nations, New York, N.Y., January 1967.

Conclusions

The task group's assessment of the likely planetary protection implications of Venus missions is as follows:

- *Landers*—The prospects for indigenous biological activity on or below Venus's surface are negligible owing to the high temperature of the surface, the absence of water, and the toxic chemical environment.[17] Similarly, the prospects for the survival of terrestrial organisms deposited by probes on Venus's surface are nonexistent. **Therefore, the task group concluded that no significant risk of forward contamination exists in landing on the surface of Venus.**
- *Atmospheric probes, including balloons*—Venus's cloud layers are an environment of moderate temperature and pressure. However, because the cloud droplets consist of concentrated sulfuric acid, any terrestrial organisms would be rapidly destroyed by chemical degradation. **Therefore, the task group concluded that no significant forward-contamination risk exists regarding the exposure of spacecraft to the clouds in the atmosphere of Venus.**
- *Surface or atmospheric sample returns from Venus to Earth*—The task group discussed in detail the recent arguments for the potential for life in the Venus cloud decks. Although it is impossible to completely rule out the possibility that life might exist in such an environment, the task group considers this possibility to be extremely low because of the hostile chemical nature of the cloud environment. Specifically, concentrated sulfuric acid is a strong dehydrating and oxidizing agent that causes the rapid destruction of complex organic molecules. And, conversely, any organisms that had managed to adapt to such a chemical environment would not find a comparable environment on Earth and would not be expected to survive. Therefore the risk to Earth posed by organisms indigenous to Venus is considered to be negligible. **Therefore, the task group concluded that no significant back-contamination risk exists concerning the return of atmospheric samples from the clouds in the atmosphere of Venus. Similarly, no significant risk exists concerning back contamination from Venus surface sample returns.**

Recommendations

In light of the above conclusions, **the task group recommends that the Category II planetary protection classification of Venus be retained.** Although there are many important scientific investigations to be carried out to improve understanding and knowledge of Venus, **the task group does not recommend any scientific investigations for the specific purpose of reducing uncertainty with respect to planetary protection issues.**

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[17] National Research Council, *Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making*, National Academy Press, Washington, D.C., 1998, pp. 31 and 77.

Attachment 1
Task Group on Planetary Protection Requirements for Venus Missions

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Attachment 2
COSPAR Categories for Planetary Protection

The Committee on Space Research (COSPAR) of the International Council for Science has defined five planetary protection categories to guide space agencies implementing solar system exploration missions. The following information describing these categories is reprinted from NASA's web site.[18]

> NASA's Planetary Protection policy calls for the imposition of controls on contamination for certain combinations of mission type and target body. There are five categories for target body/mission type combinations. The assignment of categories for specific missions is made by the NASA Planetary Protection Officer based on multidisciplinary scientific advice. The five categories are:
>
> **Category I** includes any mission to a target body, which is not of direct interest for understanding the process of chemical evolution or the origin of life. No protection of such bodies is warranted and no planetary protection requirements are imposed.
>
> **Category II** includes all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration. The requirements are only for simple documentation. This documentation includes a short planetary protection plan required for these missions, primarily to outline intended or potential impact targets; brief pre-launch and post-launch analyses detailing impact strategies; and a post-encounter and end-of-mission report providing the location of inadvertent impact, if such an event occurs.
>
> **Category III** includes certain types of missions (typically a flyby or orbiter) to a target body of chemical evolution or origin-of-life interest, or for which scientific opinion holds that the mission would present a significant chance of contamination which could jeopardize future biological exploration. Requirements consist of documentation (more involved than that for Category II) and some implementing procedures, including trajectory biasing, the use of clean rooms (Class 100,000 or better) during spacecraft assembly and testing, and possibly bioburden reduction. Although no impact is generally intended for Category III missions, an inventory of bulk constituent organics is required if the probability of inadvertent impact is significant.
>
> **Category IV** includes certain types of missions (typically an entry probe, lander or rover) to a target body of chemical evolution or origin-of-life interest, or for which scientific opinion holds that the mission would present a significant chance of contamination which could jeopardize future biological exploration. Requirements include rather detailed documentation (more involved than that for Category III), bioassays to enumerate the burden, a probability of contamination analysis, an inventory of the bulk constituent organics, and an increased number of implementing procedures. The latter may include trajectory biasing, the use of clean rooms (Class 100,000 or better) during spacecraft assembly and testing, bioload reduction, possible partial sterilization of the hardware having direct contact with the target body, and a bioshield for that hardware, and, in rare cases, a complete sterilization of the entire spacecraft. Subdivisions of Category IV (designated IV-A, IV-B, or IV-C) address lander and rover missions to Mars (with or without life detection experiments), and missions landing or accessing regions on Mars which are of particularly high biological interest.
>
> **Category V** pertains to all missions for which the spacecraft, or a spacecraft component, returns to Earth. The concern for these missions is the protection of the Earth from back contamination resulting from the return of extraterrestrial samples (usually soil and rocks). A subcategory called "Unrestricted Earth Return" is defined for solar system bodies deemed by scientific opinion to have no indigenous life forms. Missions in this subcategory have requirements on the outbound (Earth to target body) phase only, corresponding to the category of that phase (typically Category I or II).

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[18] See <planetaryprotection.nasa.gov/pp/about/categories.htm>. Last accessed February 7, 2006.

For all other Category V missions, in a subcategory defined as “Restricted Earth Return,” the highest degree of concern is expressed by requiring the absolute prohibition of destructive impact upon return, the need for containment throughout the return phase of all returning hardware which directly contacted the target body or unsterilized material from the body, and the need for containment of any unsterilized samples collected and returned to Earth. Post-mission, there is a need to conduct timely analyses of the returned unsterilized samples, under strict containment, and using the most sensitive techniques. If any sign of the existence of a non-terrestrial replicating organism is found, the returned sample must remain contained unless treated by an effective sterilization procedure. Category V concerns are reflected in requirements that encompass those of Category IV plus a continuous monitoring of mission activities, studies, and research in sterilization procedures and containment techniques.

Attachment 3
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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John A. Baross (University of Washington). Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.