Peter Mazur
Annotated

Recommendations on Quarantine Policy

for Mars, Jupiter, Saturn, Uranus, Neptune, and Titan

The National Research Council
National Academy of Engineering · National Academy of Sciences · Institute of Medicine

Committee on Planetary Biology and Chemical Evolution

Space Science Board

Assembly of Mathematical and Physical Sciences

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Foreword

The planetary missions of the past decade have multiplied our knowledge of the solar system manyfold, and those proposed for the ensuing decade will surely yield equally exciting and provocative results. Scientific prudence requires that during the course of this exploration we guard against perturbing the planets irreversibly and that we take care that ongoing missions not jeopardize future experiments or future discoveries. No discovery would be more important than that of current or past life or life-related organic molecules, and in this area general scientific prudence has been supplemented with a formal international agreement to which the United States is party. Meeting this agreement requires that the probability of contaminating the planets with terrestrial organisms be held below a specified level. The National Aeronautics and Space Administration has the responsibility for determining and taking the steps necessary to meet this policy, but it has requested recommendations from the Space Science Board on the scientific components of the problem. Until three years ago, the Board developed its recommendations through *ad hoc* committees. But since then it has assigned the responsibility for developing quarantine policy to its Committee on Planetary Biology and Chemical Evolution (formerly referred to as the Exobiology Panel). The body of the present report, which constitutes their recommendations for Mars, Jupiter, and Saturn, was reviewed by the Board in its meetings of May 27, 1977, and November 4, 1977, and was adopted unanimously. The report in Appendix C, which constitutes their recommendations for Uranus, Neptune, and Titan, was approved by the Board a year earlier (May 24, 1976) and transmitted to the Administrator, NASA. It is appended here because the Board believes that the basis of its recommendations on quarantine policy for the planets and their satellites should be a matter of public record.

A. G. W. Cameron, *Chairman*
Space Science Board

Preface

With the launching of Sputnik in 1957, it became inevitable that voyages to other planets would soon follow, voyages that were sure to search for evidence of life or for evidence of organic molecules suggestive of life. Since the scientific impact of such discoveries would be exceedingly high, it was mandatory to take precautions to reduce the chance of their being jeopardized by the contamination of the planets with terrestrial organisms. To coordinate space scientific activities, the International Council of Scientific Unions established a Committee on Space Research (COSPAR), and COSPAR obtained international agreement on a policy on outbound planetary biological contamination control.* The agreement to which the United States is a party is that "The basic probability of one in one thousand (1×10^{-3}) that a planet of interest will be contaminated shall be used as a criterion during the period of biological exploration of Mars, Venus, Mercury, Jupiter, or other planets or their satellites that are deemed important for the exploration of life, life precursors, or remnants thereof." The period of exploration has been construed to run from 1974 to 1994 and to consist of 35 landers and 15 flybys. NASA has interpreted these data to mean that, for each mission to each planet, the probability of contamination (P_c) should not exceed 10^{-6} for landers and 6.4×10^{-5} for flybys.

The likelihood of contaminating a planet depends on (1) the number and type of organisms initially on the spacecraft, (2) the fraction that survive the voyage and are released in a viable state onto the planet's surface or into its atmosphere, and (3) the likelihood that the viable organisms find themselves in areas that permit their growth and multiplication. This third component has been assigned the symbol P_g. The overall probability of contamination (P_c) is the prod-

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*We shall refer to this simply as "quarantine."

uct of (1), (2), and (3), and this product must be held sufficiently low to meet COSPAR policy. For landers and planetary probes, little can be done to adjust component (2). The duration of the voyage is fixed by celestial mechanics, and the probability of impacting the planet is we hope close to 1. Orbiters and flybys constitute no quarantine problem as long as they adhere to their expected trajectories and consequently do not impact on the planet. But trajectories that maximize scientific gain usually involve approaches close enough to the planet to raise the possibility that abnormal behavior of the spacecraft will cause it to impact.

For practical purposes, therefore, NASA has considered component (1), the initial microbial burden on the spacecraft, to be the adjustable parameter. And the higher the estimate for P_g the lower is the allowable microbial burden. As the estimated value of P_g rises, increasingly stringent measures must be taken to effect the reduction, measures that can range from sterilization of components to sterilization of the assembled spacecraft or even conceivably to preclusion of the mission.

The irony is that the very pragmatic steps that have to be taken to meet COSPAR requirements are controlled by an elusive and enigmatic quantity–P_g, the probability that a terrestrial organism can grow, multiply, and contaminate the target planet. For a planet like Venus, which has surface temperatures that exceed 500°C, P_g is clearly zero. But in the case of Mars and the more distant planets, our ignorance as to the ranges of physical and chemical environments on the planets and our knowledge that terrestrial organisms possess amazing abilities to function in a wide variety of terrestrial environments combine to make the estimation of P_g vexatious and inexact.

It will be evident in reading the Committee's analyses in the body of the report and in Appendix C that another problem in estimating P_g is that the estimates have had to be based largely on epidemiological and probabilistic considerations. As pointed out by Margulis *et al.* (Appendix C and Reference 3), the experimental approach to planetary quarantine has been slighted. There have, for example, been no experiments to determine whether any terrestrial organisms can be found that will grow in aerosol droplets suspended in the high concentrations of hydrogen and methane that prevail in the Jovian atmosphere.

In spite of the difficulties and uncertainties, decisions by NASA on quarantine procedures for planetary missions demand numerical values for P_g. Accordingly, the Space Science Board over the past three years has assigned our Committee the responsibility of making recommendations on P_g for the five planets lying between earth and Pluto. Since other committees had previously estimated P_g for Mars, Jupiter, and Saturn, since the present Voyager mission is to fly by Titan, and since it includes a Uranus option, the first task assigned to us was to estimate P_g for Uranus (and Neptune) and Titan. These estimates, which are given in Appendix C, were approved by the Board and transmitted to the Administrator of NASA in May 1976. The subsequent initiation of work on a Jupiter orbiter with probe (JOP) and the return of major new information on Mars by the highly successful Viking missions led NASA then to request a revaluation of the earlier estimates of P_g for Jupiter, Saturn, and Mars. These revised estimates are given in the body of this report.

Estimations of the probability of growth required us to develop a relationship between knowledge of terrestrial microbial function under terrestrial environmental extremes and knowledge of the physical and chemical conditions found on the target planets. Acquisition of information on the biological aspects was aided by the scientific backgrounds of the members of the Committee. The acquisition of information on the target planets proceeded in two ways. Information on conditions on Mars was gained by the Committee in the course of preparing its recent report *Post-Viking Biological Investigations of Mars.* Information on conditions on the outer planets was obtained chiefly through the participation of two planetary astronomers (A. G. W. Cameron and John Lewis) in an *ad hoc* committee chaired by Lynn Margulis. The relationships between terrestrial biology and planetology that comprise this report were developed during some six meetings of the Committee and invited consultants. Among the latter we wish especially to thank R. Young and N. Horowitz. The Committee also wishes to acknowledge the valuable contributions of its Executive Secretary, Milton W. Rosen, and his staff in organizing our meetings and in the preparation of our report.

Peter Mazur, *Chairman*
Committee on Planetary Biology
and Chemical Evolution

Space Science Board

Committee on Planetary Biology and Chemical Evolution*

Peter Mazur, *Chairman*
Oak Ridge National Laboratory

Elso S. Barghoorn
Harvard University

Harlyn O. Halvorson
Brandeis University

Thomas H. Jukes
University of California, Berkeley

Isaac R. Kaplan
University of California, Los Angeles

Lynn Margulis
Boston University

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*Formerly Exobiology Panel.

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Introduction

Planetary missions are required to meet the internationally agreed upon COSPAR planetary quarantine policy, which calls for a probability of contamination (P_c) of $<1 \times 10^{-3}$ for each planet over the 20 years 1974 to 1994. The probabilistic formulation used by NASA to estimate P_c includes P_g, the probability that a terrestrial organism could be deposited on the planet and grow. The current NASA estimate of P_g for Mars required terminal heat sterilization of the Viking Landers and would require comparable sterilization of future Landers. Since the present policy might also limit the scientific return from the Viking Orbiters during the extended Viking mission by putting constraints on the minimum permissible periapsis of these unsterilized crafts, NASA requested that the Space Science Board and its Committee on Planetary Biology and Chemical Evolution re-evaluate the current quarantine policy on Mars in light of the findings from Viking and that it recommend a new policy if appropriate.*

At the same time, a request* was made by NASA for a reassessment of the probability of growth (P_g) of terrestrial microorganisms on Jupiter and Saturn. NASA has currently adopted a value of $P_g = 10^{-7}$ based partly on prior recommendations of the Space Science Board. The Board's recommendations were, in turn, based on the probability of the growth of terrestrial microbes on Jupiter and Saturn estimated by an *ad hoc* SSB Committee (R. Goody, N. H. Horowitz, and A. Rich) in 1974. The committee's estimate was derived by assigning a probability of 10^{-1} that an organism released into the Jovian or Saturnian atmosphere would be an anaerobe and a proba-

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*See Appendix D, letter from Associate Administrator, NASA, to Chairman, SSB, and Appendix E, letter from Chairman, SSB, to Associate Administrator, NASA.

bility of 10^{-6} that such an anaerobe would grow. Our more recent analyses of this problem and new data suggest that this earlier estimate of the probability of growth of microorganisms on Jupiter and Saturn is too high. Therefore, a reassessment is appropriate.

In a previous report on *Recommendations on Quarantine Policy for Uranus, Neptune, and Titan*, Appendix C, we stated "that the probabilistic basis underlying COSPAR quarantine policies is inadequate," and that "it underemphasizes the experimental search for terrestrial organisms capable of growth under conditions believed to exist on target planets." Alternative experimental approaches have been proposed (Appendix C and Reference 3), and we recommend that they be pursued. Nevertheless, at present the United States is committed to the probabilistic approach underlying COSPAR policy, and there is as yet no quantitative and operationally useful alternative.

2

Recommendations on Quarantine Policy for Mars Based on the Current Viking Findings

The current NASA policy on the likelihood of growth of terrestrial microorganisms on Mars is based on the December 14, 1970, Space Science Board report, *Review of Sterilization Parameter Probability of Growth (P_g).*

The report established the minimum conditions necessary to define a microenvironment on Mars that would support growth of the most "hardy terrestrial organisms." The conditions established were the following:

(a) Water activity (a_w) $\geqslant 0.95$.

(b) Temperature $\geqslant 0°$ C for at least 0.5 h/day.

(c) Nutrients: At least small amounts of water-soluble nitrogen, sulfur, phosphorus, carbon (and/or light). pH values between 5 and 8.

(d) Attenuation of uv flux by more than 10^3.

(e) Antinutrients–absence of antimetabolites.

All the above conditions must occur simultaneously, or nearly so.

The report then proceeded to estimate the value of P_g, the "estimated probability that growth and spreading of terrestrial organisms on the planet surface will occur." The estimated value of P_g was 3×10^{-9}, with less than one chance in a thousand that it exceeded 1×10^{-4}. For the Viking project, NASA adopted a value of $P_g = 10^{-6}$, some three orders of magnitude more favorable to growth than the best estimate of the review committee, but still two orders of magnitude less than the extreme upper limit. The adoption of this value required terminal heat sterilization of the entire Viking Lander but not of the Orbiter. The value remains NASA policy to date.

I. VIKING FINDINGS PERTINENT TO QUARANTINE

Estimating the likelihood of the growth of terrestrial organisms on Mars requires a comparison between the known physical and chemical limits to terrestrial growth and the known and inferred conditions present on or just below the Martian surface. Table 1 makes that comparison in abbreviated form. Appendix A discusses in fuller form the inferences that can be drawn from the Viking findings about those physical and chemical characteristics of the Martian surface that are pertinent to the question of the growth of terrestrial microorganisms.

Orbital measurements have covered appreciable fractions of the planet's surface, but the two Landers (VL-1 and VL-2) have sampled only a few square meters of the surface at two subpolar sites. The biologically relevant experiments were conducted on soil samples acquired during the Martian summer and early fall from as deep as 6 cm below the surface. (In March 1977 a sample was acquired from a depth of 20 cm, but as of April 1977 an inorganic analysis is the only experiment that has been performed.) Nevertheless, certain extrapolations relevant to the quarantine question can be made with various degrees of confidence to other regions of the planet, to greater depths, and to other seasons of the year.

TABLE 1 Limits for Growth of Terrestrial Organisms

Factor	1970 Study	Refs. 2 and 3	Conditions on Mars[a]
Water activity (a_w)	$\geqslant 0.95$	>0.9	0 to 1
Water (liquid)	–	Required	Not detected
Temperature	$\geqslant 0^\circ C$	$>-15^\circ C$	$+20$ to $-143^\circ C$ (see text)
pH	5-8	<11.5	Not known
Ultraviolet radiation[b]		$0.1\ J\ cm^{-2}$	$0.04\ J\ cm^{-2}\ min^{-1}$
Ionizing radiation[b]	–	2-4 Mrad	<500 rad/yr[c]
Nutrients	See text and Refs. 2 and 3		Organic compounds $\leqslant$ppb; most required elements detected (see text)[d]
Antimetabolites	None present		Strong oxidants present (see text)[d]

[a] Cf. Reference 1; uv flux data from Reference 18.
[b] Limit for survival. Limits for growth are not known.
[c] See p. 11.
[d] At VL-1 and VL-2 sites.

II. CONCLUSIONS ON THE LIKELIHOOD OF THE GROWTH OF TERRESTRIAL ORGANISMS ON MARS

We turn now to a reassessment of P_g, the likelihood of the growth of terrestrial organisms on Mars. We will consider three regions separately: (1) subpolar areas within a few centimeters of the surface, (2) subpolar regions more than a few centimeters below the surface, and (3) the residual polar caps. Finally, we will discuss briefly the likelihood that terrestrial organisms could survive transport at or above the surface from one region to another.

A. Subpolar Regions within about 6 Centimeters of the Surface

Our conclusion is that no terrestrial organisms could grow within a few centimeters of the surface in the regions lying between the two residual polar caps. We base this judgment on the following of the Viking findings:

– The presence in VL-1 and VL-2 sample of strong oxidants.

– The absence of detectable organic compounds, which (a) attests to the power of the oxidants and (b) renders unlikely the existence of the specific types of organic compounds required for terrestrial heterotrophic organisms.

– The inability of physical shielding by a rock to eliminate the oxidants.

Our conclusion is reinforced by three additional factors that were well known before the mission:

– The unlikelihood of organisms being deposited in regions that receive sufficient visible light to support photosynthetic autotrophy without at the same time receiving lethal fluxes of ultraviolet radiation.*

– The exceedingly low probability for the existence of liquid water with activity (a_w) high enough to support terrestrial growth.

– The fact that, even if liquid water were present, vegetative cells would be subjected to daily cycles of injurious freezing; and only vegetative cells can grow.

*Although unlikely, the probability is not zero. Sagan and Pollack[10] have calculated that, although the uv flux is attenuated several millionfold at 0.8 cm below the Martian surface, the flux of visible light would still be 3.8×10^2 erg cm^{-2} sec^{-1} at that depth.

It is highly likely that the surface conditions enumerated above at the VL-1 and VL-2 sites prevail over the subpolar regions of the planet. This conclusion is based on

1. The similarity in the findings at two widely separated points for the elemental composition of the regolith and for the results of the organic analysis and the gas-exchange experiments.
2. The strong probability that the oxidants are derived from atmospheric reactions or atmosphere–regolith reactions. Accordingly, it is difficult to conceive of regions that would be accessible to terrestrial microorganisms and at the same time be capable of excluding the atmosphere.
3. The fact that the Infrared Thermal Mapper (IRTM) has mapped a sizable fraction of the Martian surface without detecting thermal heterogeneities significantly more favorable to terrestrial growth than those that we have reviewed in Appendix A.

Viking has provided much information that was either not known beforehand or was known only with considerable uncertainty. None of this new information suggests that the Martian surface is less harsh to terrestrial microorganisms than was thought prior to Viking.* On the other hand, two pieces of information indicate that it is harsher than was thought previously: the lack of detectable organic compounds and the presence of strong oxidants even in regions physically shielded from uv.

Our conclusion is that no terrestrial organism could grow under the conditions found by Viking to prevail on subpolar surfaces at the landing sites and none could grow under the conditions that are highly likely to prevail throughout the entire subpolar region. Few if any terrestrial organisms could grow in contact with even one of the adverse conditions cited, much less grow when exposed to all of them simultaneously. Although we cannot absolutely rule out the existence of oases capable of supporting terrestrial life, we believe, for the reasons cited, that the likelihood of their existence is extremely low.

Unfortunately, we know of no quantitative basis for assigning a numerical probability to "extremely low" when no oasis has been

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*The demonstration by Viking that the atmosphere contains nitrogen answers an important question that was unknown previously. However, the ignorance prior to Viking of the existence of nitrogen was not a significant factor in prior estimates of the probability of growth of terrestrial organisms.

detected and when the weight of evidence is that none can exist. And yet a numerical value for P_g is required in order to determine what procedures are needed to reduce the microbial burden on future spacecraft to Mars to levels that fulfill current COSPAR quarantine policy. Reluctantly, then, *we recommend for these purposes, and these purposes alone, that NASA adopt a value of* $P_g < 10^{-10}$ *for the subpolar regions of the planet within 6 cm of the surface.** This number, which is more than four orders of magnitude below the current value of P_g, reflects the fact that Viking has found the conditions to be considerably harsher to terrestrial life than was heretofore assumed and has obtained evidence that renders the existence of oases far less likely than was heretofore assumed.

B. Regions More than 6 Centimeters below the Surface of Subpolar Regions

As mentioned, Viking conducted biology experiments and organic analysis on samples obtained from depths of 4–6 cm. Greater depths would be required to reduce or eliminate the lethal surface conditions. The depths required are unknown chiefly because the relation between depth and the presence of oxidants is unknown. However, the maximum temperature falls rapidly with depth. In the northern hemisphere, even at a depth of 4 cm, the maximum temperature is estimated to be 20° below the minimum confirmed growth temperatures (−15°) observed for terrestrial organisms (Appendix B). By a depth of 24 cm, the *maximum* temperature is estimated to be −50°C, some 35° below the minimum confirmed terrestrial growth temperature. In the southern hemisphere, the *maximum* temperature at a depth of 24 cm is estimated to be −35°C, still 20° below the minimum terrestrial growth temperature.[4,8]

At increased depths there is an increased likelihood of encountering ice, the existence of which would enhance the possibility of liquid water. But water that is liquid below −20°C and is in equilibrium with ice has an activity (a_w) below that which will support the

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*We obtain this value by estimating probabilities of $<10^{-2}$ for the presence of liquid water of high enough a_w, $<10^{-1}$ for the ability to survive multiple freezing and thawing, $<10^{-1}$ for the avoidance of lethal uv, $\ll 10^{-2}$ for the presence of organic compounds of appropriate types in appropriate concentrations, $\ll 10^{-3}$ for the absence of powerful oxidants, and 0.1 that the deposited microorganism is an anaerobe.

growth of any known terrestrial organism capable of growing under the partial pressure of oxygen on Mars (Appendix B, Figure B.2).[9]

Thus, temperature alone seems an absolute barrier to the growth of any terrestrial organisms at depths below a few tenths of a meter. But again, sufficient uncertainties exist to preclude an absolute statement to this effect; viz.,

– Although the surface temperatures are derived directly from the orbital infrared measurements and are consistent with the direct meteorological measurements at the landing sites 1.5 m above the surface, the estimates of subsurface temperatures require assumptions about the thermal diffusivity of the soil. The range of error is estimated by Kieffer[8] to be 5°C. This error would not be sufficient to change our conclusions, but larger errors are conceivable.

– There could exist heterogeneities below the resolving power of the IRTM (a minimum of 2 km) that have higher temperatures.

– Although there is extensive information on the minimum growth temperatures of terrestrial microorganisms, the remote possibility exists that some unknown organism has a growth minimum below $-15°C$. We view this as extremely remote because, as indicated in Appendix B, the number of species capable of growth diminishes drastically as the temperature is lowered below 0°C. Furthermore, growth below $-15°C$ is tantamount to growth in $\geqslant 8$ osmolal solute, conditions that even at ordinary temperatures preclude the growth of all except halophiles and osmophiles.

– There is the remote possibility that there exists somewhere a narrow zone of subsurface that is deep enough to preclude oxidants and shallow enough to have temperatures high enough to support growth.

Although these uncertainties prevent us from concluding that the possibility for growth is zero, we are still forced to conclude that subsurfaces of Mars are exceedingly harsh for terrestrial life. Accordingly, *for the specific purpose of determining quarantine requirements for future Martian missions, we recommend that NASA adopt a value of* $P_g < 10^{-8}$ *for subsurfaces in the subpolar regions of the planet.*

C. The Residual Polar Caps

The arguments just presented for subsurface regions generally apply to the residual polar caps as well. As in the subsurface regions, the temperatures mapped by the IRTM are too low to permit the growth of known terrestrial organisms. However, thermal heterogeneities have been detected. The maximum temperatures observed (237 K) are not high enough to permit the growth of earth organisms, but their presence raises the remote possibility that there exist other undetected heterogeneities for which the temperature does rise high enough. But warmer regions will also be drier regions, because the increased vapor pressure associated with higher temperatures would cause water to distill rapidly from these regions and freeze out at the cold trap furnished by the remainder of the residual cap.[4] The water ice itself in the residual caps constitutes a possible source of liquid water, provided that special conditions were present to permit that ice to liquefy rather than to sublime (e.g., freezing point depression by electrolytes). But even then, as in the case of subsurfaces, the temperatures would be too low to permit the growth of terrestrial organisms.

The polar regions would not be immune from the atmospheric oxidants, but chemical interactions between atmosphere and ice might be different from chemical interactions between atmosphere and regolith.

Our conclusions about the likelihood of growth in the residual polar caps are similar to those reached in Section B above for subsurface subpolar regions—it is extremely low. Nevertheless, because there is more uncertainty about the physical and chemical conditions at the residual polar caps, we believe that these regions should be handled with prudence and *recommend that they be assigned a value of* $P_g < 10^{-7}$.

D. Transport from Subpolar Regions into the Residual Polar Caps or into Putative Oases

There is little likelihood that any terrestrial organism could survive a voyage on or above the surface requiring more than a few minutes. First, the uv flux on the surface of Mars is 4×10^{-2} J cm^{-2} min^{-1}, and that flux would kill the most resistant of terrestrial microorganisms in a few minutes (upper terrestrial limit 0.1 J/cm^2) (Table 1). Second, organisms protected from the direct exposure to the uv by a layer of soil particles would nevertheless be in contact with the oxidants in those soil particles.

One consequence of these lethal conditions is that our recommended value of $<10^{-7}$ for P_g in the residual polar caps applies only to terrestrial organisms that are released directly in that region. The P_g for organisms transported into the polar caps from the subpolar regions would be orders of magnitude lower. Similarly, even if Mars were to possess oases that were hospitable to terrestrial life, few if any terrestrial organisms would survive a surface or aerial trip to the oasis and few if any would ever survive an escape from the oasis.

III. LIMITS TO THE GROWTH OF TERRESTRIAL LIFE VERSUS THE QUESTION OF INDIGENOUS LIFE ON MARS

The evidence that leads us to the conclusion that terrestrial microorganisms have little and in most regions of the planet no probability of growth does not rule out the possibility that indigenous life forms may exist currently on Mars or may have existed sometime in the past. The limiting conditions listed in Table 1 for terrestrial life are not the limits for conceivable life elsewhere.

There is fairly wide agreement that life, if it exists elsewhere, is based on carbon chemistry and that it requires nitrogen; organic compounds of high information content, energy, and substrates to permit the synthesis of the organic compounds; and liquid water. Although, as discussed, organic compounds and liquid water have not been detected on Mars, there is no basis for precluding their existence. There is, moreover, strong evidence that liquid water in large quantities existed in the Martian past.

It might be argued that, if indigenous life forms do exist, they themselves could constitute micro-oases for the growth of terrestrial organisms. We consider this unlikely. For example, a Martian organism growing in thermal equilibrium with its surroundings at -40°C would be of no value to a terrestrial organism incapable of growing below 0°C. A Martian organism that maintains its temperature at 0°C even when the external temperature is -40°C is conceivable. However, to do so, a spherical organism 2×10^{-4} cm in diameter, for example, encased in efficient insulation $\geqslant 1$ mm thick would have to assimilate and burn about 1000 times its steady-state concentration of organic compounds *per second* to maintain the 40-degree differential. The problem would be only slightly less serious in a macroscopic Martian organism. Analogous difficulties arise in postulating that the organic compounds in putative Martian biota would be compatible with and utilizable by the enzyme systems of terrestrial microorganisms.

TABLE 2 Estimated Contributions to P_g for Jupiter and Saturn

Factor	1974 Jupiter Report	1976 Uranus Report	Comments
Temperature	1	1	Assumed between -20 to 100°C
Pressure	1	1	Not a critical parameter for microbiology
Radiation	1	Not specified but <1	Deleterious
Liquid H_2O	1	1	Assumed
Nutrients	10^{-1}	$<10^{-3}$[a]	Organics, ions = aqueous solution
Anaerobiosis	10^{-1}	10^{-1}	About 0.10 of the earth's microbes are anaerobes, but these are unlikely to be spacecraft contaminants
NH_3 toxicity	10^{-2}	$<10^{-4}$[b]	
Growth in aerosols	Not specified	$<10^{-3}$[a]	Completion of life cycle in the atmosphere has never been reported for any earth organisms
Convection to lethal temperatures	10^{-3}	$<10^{-3}$	All models predict that organisms will be carried from water levels to lethal depths; the times required are somewhat model dependent
TOTALS	10^{-7}	$<10^{-14}$	

[a] Based on more detailed analyses.[2,3]
[b] New information, e.g., Reference 22.

IV. CONCLUSIONS PERTINENT TO THE CURRENT VIKING ORBITERS

As of August 1977, two years have elapsed since the unsterilized Orbiters were launched from earth. Any organisms on the outer surface of the Orbiter have surely been killed by uv irradiation. Most organisms in the interior of the Orbiter have been subjected to moderate temperatures (10 to 38°C), high vacuum, and some ionizing radiation.[11] Although the cell dehydration associated with the high vacuum would be lethal to a fraction of the microbial population, many (perhaps 1 to 10 percent) would likely survive.[6,12,13] Some protons from galactic cosmic rays and solar flares would strike organisms in the interior, but the dose would be appreciably less than 500 rad/year,[11,14] and many microorganisms can survive such doses. (The flux of solar protons far exceeds that from galactic source, but the great bulk of the solar protons have energies of $\leqslant 1$ MeV,[11] and such protons are only capable of penetrating $\leqslant 0.1$ mm of material with a density of 1, e.g., water.[14]) Conservatively, then, one cannot assume that the microbial burden within the Orbiter has decreased by more than 1 or 2 orders of magnitude since launch.

In spite of the expected survival of a fraction of the original burden of terrestrial microorganisms, our new estimates of the values of P_g lead to the conclusion that COSPAR requirements for planetary quarantine will not be compromised by lowering the periapsis of the Orbiters to 300 km. Indeed, with the new values for P_g, still lower periapses for unsterilized Martian orbiters may well be compatible with COSPAR requirements. NASA will probably wish to determine these minimum orbital altitudes before assessing and designing Mars follow-on missions in detail.

V. QUARANTINE STRATEGY FOR FUTURE MISSIONS TO THE MARTIAN SURFACE

Our Committee has recommended that the next phase in the biological exploration of Mars should be to acquire and characterize soil samples from areas likely to contain sediments and ice–regolith interfaces.[1] Locating these areas and locating sites that are shielded from the powerful atmospheric ultraviolet radiation and the powerful surface oxidants will require subsurface sampling by a soft lander, by penetrators, or by both. The samples acquired from the subsurface of Mars should be characterized with respect to organic compounds, carbon and sulfur isotope ratios, the amount and state of water, the presence of water-soluble electrolytes, and the existence of non-equilibrium gas compositions. The greater the extent to which samples possess these characteristics the greater the priority for the initiation of a second phase of post-Viking biological exploration of Mars—a detailed search for evidence of present or past life on Martian samples returned to earth.

With respect to quarantine considerations for the mission that conducts the first exploratory phase, our estimates for the values of

P_g lead to the conclusion that terminal heat sterilization would not be required in the case of a nominal soft landing in the subpolar regions (Section A) and possibly in other cases as well. However, we would have no objections to sterilization *provided that* it has no impact on the scientific payload of the landers and that it does not increase the mission cost. (We have been informed by representatives of NASA that this may be the case.) Decisions on scientific payloads for the missions should be based on their scientific quality and cost effectiveness. *We would object to the elimination of an experiment or the degradation of its performance because of the imposition of unessential sterilization requirements.*

In the report *Post-Viking Biological Investigations of Mars*,[1] we stated that we consider metabolic-type life-detection experiments on the surface of Mars to be of low priority scientifically. Nevertheless, NASA may decide to include them. If so, a limiting factor with respect to the allowable microbial burden on a soft lander would likely become the avoidance of contaminating the metabolic experiment by terrestrial microorganisms.

3

Revised Recommendations on Quarantine Policy For Jupiter and Saturn: Limits to Growth of Earth Microorganisms on the Outer Planets

In response to a March 1975 request from the Associate Administrator for Space Science, NASA, the Space Science Board asked its Exobiology Panel* to make recommendations on quarantine policy for Uranus, Neptune, and Titan. The Panel's recommendations, which were approved by the Board and transmitted to the Administrator, NASA, on May 28, 1976, are given in Appendix C. The scientific basis for the recommendations was developed by an *ad hoc* committee consisting of Lynn Margulis, Chairman, A. G. W. Cameron, H. O. Halvorson, and John Lewis. Their findings are given in Appendix C. They were also published in expanded form.[3]

The *ad hoc* committee extensively analyzed the chance of growth of terrestrial microorganisms in the atmospheres of the outer planets. Their and our conclusion was that the probability of growth of microorganisms on Uranus and Neptune is nil ($<10^{-14}$). Present ground-based and Pioneer observations indicate that the physical conditions on all four outer planets with respect to parameters affecting biology are probably closely comparable. Thus, the arguments first generated in the context of microbial contamination of Uranus and Neptune apply without essential change to Jupiter and Saturn. *We, therefore, conclude that the probability of growth of earth microorganisms on Jupiter and Saturn is also nil* ($<10^{-14}$).

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*Later renamed the Committee on Planetary Biology and Chemical Evolution.

spacecraft might compromise the function of the spacecraft or its scientific payload (Appendix C).

Except for Titan, the Committee has not considered the satellites of the outer planets. For Titan, the Committee recommended a tentative value of P_g of 10^{-10} (Appendix C).

Virtually all models of the Jovian planets agree that hydrogen gas is a predominant constituent of the atmospheres. Our estimate of P_g has not included possible effects of high hydrogen concentrations on the growth of potential contaminant organisms. Careful studies designed to select terrestrial microbes capable of growth in high pressures of H (and CH_4) are lacking. We suggest that these experiments would not only add valuable information to basic microbiology but might provide results immediately applicable to planetary quarantine as well.