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Planetary Contamination I: The Problem and the Agreements

Mars is more hostile than had been supposed; quarantine constraints should be eased accordingly.

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It has been recognized that microorganisms carried on spacecraft could, under certain conditions, contaminate the planets, with a resulting loss of unique and invaluable scientific information (*1*). Mars has seemed particularly vulnerable to contamination, Venus somewhat less so. Martian conditions, although extremely hostile, do not preclude the existence of an indigenous form of life (*2*). The apparently high surface temperature of Venus would exclude any form of life over most of the planet, but some observers believe that more equable conditions may be found on mountain tops or in the polar regions (*3*). The presence of water in the Venus (*4*) and Mars (*5, 6*) atmospheres has been established.

These considerations have led to the formulation of recommendations concerning planetary quarantine and spacecraft sterilization by an international body, the Committee on Space Research (COSPAR) of the International Council of Scientific Unions. Both the United States and the U.S.S.R. are represented on COSPAR. The current recommendations are contained in a resolution adopted in 1964 (*7*), according to which COSPAR

> accepts, as tentatively recommended interim objectives, a sterilization level such that the probability of a single viable organism aboard any spacecraft intended for planetary landing or atmospheric penetration would be less than 1×10^{-4}, and a probability limit for accidental planetary impact by unsterilized fly-by or orbiting spacecraft of 3×10^{-5} or less.

A U.S. recommendation to relax the constraint on heat-sterilized Mars landers to 1×10^{-3} was made at the 1966 COSPAR meeting (*8*). This change would not affect the argument of the present article.

Although seldom mentioned, there is another reason for sterilizing landers which is independent of the need to avoid planetary contamination; that is the need to prevent confusion of life-detection experiments performed by the lander. For this purpose, only surfaces in contact with the atmosphere need be sterilized, since only organisms on such surfaces would have access to the outside. This is a less stringent demand than that of the COSPAR resolution, which requires sterility of the interiors of solids and sealed spaces as well.

Implementation of the COSPAR resolution is not a trivial matter. In effect, the resolution requires that less than one viable microorganism be contained in each 10,000 spacecraft intended for planetary entry. Attainment of such a goal demands heroic measures, and current U.S. directives call for dry-heat sterilization of the completely assembled lander stage (*9*). To heat-sterilize a system as intricate as a spacecraft without degrading its reliability or functional lifetime is a unique problem requiring the development of a new and costly technology. The difficulty is compounded by urgent recommendations for landing an automated biological laboratory on Mars (*10*). Very complex Mars landers on the one hand and virtually total sterility on the other are conflicting goals.

Because serious practical problems are raised by the COSPAR recommendations, an examination of the premises of these recommendations in the light of current knowledge of the Martian environment is desirable. This article attempts such a reassessment. Venus presents a different problem and is not considered here. In the article by Murray, Davies, and Eckman which follows (see p. 1505), U.S. and Soviet attempts to implement the COSPAR agreements are reviewed.

Origin of the Quarantine Constraints

Since both sterilization and infection have the character of random processes, the planetary quarantine problem is usually discussed in probabilistic terms. In an early paper (*11*), Davies and Communtzis proposed that the value 10^{-6} be adopted as the maximum acceptable risk, per mission, of contaminating the planets. No attempt was made to translate this value into numbers of organisms per spacecraft. Subsequently, Jaffe (*12*) arrived at an acceptable contamination risk of 10^{-4} per Mars mission performed during the period of unmanned exploration; the probability of contamination following the first manned landing (which, it is generally assumed, will occur between 1985 and 2000) was considered to be high. Jaffe, evidently believing that every organism aboard a spacecraft would be capable of multiplying on Mars, recommended that 10^{-4} be adopted as the upper limit on the probability of carrying a single viable organism aboard any Mars lander or entry capsule.

A detailed mathematical model for a Mars quarantine policy has recently been presented by Sagan and Coleman (*13*). This model is of particular concern in the present context because

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it furnished the theoretical basis for the COSPAR resolution. Several alternative mathematical analyses—essentially refinements of the Sagan-Coleman treatment—have been carried out (*8, 14*). It is not our purpose to compare these various models. Rather, we wish to examine the physical and biological premises underlying the COSPAR-recommended constraints. If these contraints are unnecessarily severe, as we believe they are, this is not the result of deficiencies in the mathematical model but is the result of unrealistic physical and biological assumptions.

The Sagan-Coleman derivation leads to the following result for p, the probability that N biological experiments are performed on Mars before the planet is contaminated:

$$\ln p^{-1} \simeq \frac{\sigma\, NP_m}{\chi P_e P_t P_l} + nP_i \qquad (1)$$

where σ is the number of viable microorganisms deposited on the surface of Mars; P_m is the probability that an organism so deposited will multiply and contaminate a significant fraction of the planet; χ is the average number of biological experiments performed per landing capsule; P_e is the mean probability that a given experiment will succeed; P_t is the probability that the spacecraft will operate as planned; P_l is the probability that a form of life detectable by the experimental package is within reach of the lander; n is the number of unsterilized flybys and orbiters in the program of Martian exploration; and P_i is the probability of planetary impact by such an orbiter or flyby. The first term on the right-hand side of Eq. 1 thus refers to landers, the second refers to orbiters and flybys; these two terms are assumed to be equal.

The constraint 10^{-4} placed on planetary entry probes by COSPAR is σ of Eq. 1, and the value 3×10^{-5} refers to P_i. No documentation is provided by COSPAR to justify these numbers. It is known, however, that they were derived, with slight corrections, from the paper of Sagan and Coleman (*13*). We therefore refer to this paper for their vindication.

Sagan and Coleman propose the following numerical values for the parameters of Eq. 1: $p = 0.999$, $N = 10^3$, $P_m = 10^{-2}$, $\chi = 20$, $P_t = 0.9$, $P_eP_l = 0.1$, and $n = 30$. In addition, it was decided that σ, the number of organisms deposited on the surface of Mars, should be taken as equal to the total number of organisms aboard the landed spacecraft. All these assumptions are reflected in the COSPAR recommendations. The probability p represents a value judgment, or as Light *et al.* have termed it (*8*), the "level of commitment" to a quarantine policy. The other parameters are subject to objective discussion and reevaluation as knowledge of the relevant engineering and scientific factors improves. The recent increase in our knowledge of Mars coming from Mariner 4 and Earth-based observations emphasizes the need for a critical reassessment of P_m, the probability that a terrestrial microorganism will contaminate Mars. New studies also throw doubt on the assumption that all microorganisms aboard a landed spacecraft will have access to the surface of Mars. In the following sections we consider the questions of transport of microorganisms to Mars, their release from a landed spacecraft, and their survival and growth under Martian conditions.

Interplanetary Transport and Release of Microorganisms

There is reason to believe that a substantial fraction of the spores and vegetative bacterial cells aboard a spacecraft would survive the journey to Mars. The only significant lethal factor of the interplanetary environment is solar radiation. Microorganisms exposed to unfiltered sunlight would be killed rapidly, but only a small part of the microbial population of a spacecraft is in exposed locations. The possibility of a lethal effect from the vacuum of space has been tested in several studies on the survival of spores and vegetative bacteria in ultrahigh vacuum (10^{-7} to 10^{-10} torr) for periods of up to 137 days (*15*). The results show that, in high vacuum at ordinary temperatures, microbial cells not only survive but are preserved. These findings are consistent with a large body of data on the effects of drying bacteria under low vacuum.

The microorganisms aboard a landed spacecraft will not all have equal access to the planet. Those located on surfaces in contact with the atmosphere will have a significantly better chance of being carried off the spacecraft than those trapped in the interior of solids or in hermetically sealed spaces. But organisms on exposed surfaces of landers carrying life-detection experiments must be eliminated in any case, for the reason given above. This can be accomplished by gaseous sterilization or brief heating, treatments which are not seriously damaging to the spacecraft. Prolonged heat sterilization is required only to destroy organisms that are isolated from the atmosphere. The use of drastic sterilization procedures thus rests on the presumption that entrapped organisms pose a significant hazard to the ecology of Mars. Let us now consider this question.

We note at the outset that most electronic parts appear to be internally sterile, or very nearly so. Tests on components of various types—transistors, diodes, capacitors, resistors, cores, and chokes—have shown microbial contamination in only about 10 percent of several hundred items checked (*16*). This result is not surprising, since many electronic parts are heated to sterilizing temperatures in the course of their manufacture or testing (*17*). Certain other components, such as solar panels, which are known to be contaminated, could be manufactured or treated in such a way as to reduce or eliminate the bacterial load, if it were desired to do so (*18*).

The release of microorganisms from sealed components of a spacecraft requires physical disintegration of the spacecraft, such as might occur in a crash landing. Given the low degree of contamination of electronic parts noted above, it can be shown that extensive fragmentation of the lander into submillimeter-sized particles must occur before there is a significant probability of releasing microorganisms onto the surface (*19*). The chance of an accidental crash landing is assumed by Sagan and Coleman to be $1-P_t<.1$, a reasonable estimate. Given the low probability of a crash landing, one must ask why these authors adopt the premise that all organisms aboard a landed spacecraft, whether on exposed surfaces or within solids, have an equal chance—assumed to be unity—of reaching the surface of Mars. Two arguments are advanced for this view: first, that microorganisms may diffuse through solids with time scales of the order of a decade; and second, that microorganisms may be released from within solids by eolian erosion. The notion that organisms may diffuse through solid materials is based on a misunderstanding (*20*). There is no foundation for this assumption, either in experiment or in theory (*21*). The suggestion that erosion by wind-driven particles may effect the release of microorganisms merits consideration, however.

The principal agents of eolian erosion are saltating (hopping) particles. Particles so heavy that they move in constant contact with the ground, or so fine that they remain suspended in the atmosphere, have negligible erosive power. Indeed, particles of the former class—those that are rolled or pushed along the ground—are countererosive in that they tend to bury and protect objects in their path. Under known or postulated conditions of surface-roughness, gravity, particle density, and atmospheric pressure and density, it is possible to calculate the minimum wind velocity and optimum particle size for initiation of grain movement (*22–24*). For the earth, the optimum particle size is about 0.1 millimeter diameter, and the required wind velocity is 16 to 18 kilometers per hour. On Mars, owing largely to the lower atmospheric density, the optimum particle diameter is approximately 0.7 millimeter, and the requisite velocity is 145 kilometers per hour at an atmospheric pressure of 25 millibars (*23*). Extrapolation to a 10-millibar pressure, which is more realistic, shows the required velocity to be in the neighborhood of 250 kilometers per hour (*25*). These estimates are for the initiation of particle motion by traction (rolling); to initiate saltation may require still higher velocities.

Direct observations of cloud movements on Mars do not indicate ground-level wind velocities (*24, 26*) of the magnitude needed to move grains. The yellow clouds sometimes seen on Mars (*27*) are usually interpreted as wind-blown dust. Öpik, however, has argued that these clouds may be generated not by winds but by asteroidal impacts (*28*). Gifford (*24*) concludes that saltating particles accompany the yellow clouds, but his calculation of the requisite wind velocity differs from that derived from empirical data by Bagnold (*22*), being lower by a factor of 2 to 4. A recent theoretical treatment by Leovy (*29*) permits an inference of maximum wind velocities of 80 to 160 kilometers per hour at the Martian surface, probably too low to initiate grain movement.

Öpik has estimated eolian erosion rates on Mars from the frequency curve of crater diameters observed in the Mariner 4 flyby (*28*). He concludes that erosion rates are less for Mars than for terrestrial deserts by a factor of 30. He calculates that, on Mars, a rocky formation 2 kilometers high could be leveled by erosion in 4.5 billion years—that is, could erode at a rate of 4.5×10^{-4} millimeter per year. By way of comparison, Öpik states that stone sphinxes in the Egyptian desert have eroded at a rate of about 5 centimeters in 3000 years, or 1.7×10^{-2} millimeter per year (*30*). Erosion of lucite rods in an area of intense sandblasting in the California desert attained a maximum rate of just under 1 millimeter in 10 years; crystalline rocks showed no detectable effects in the same period (*31*). These erosional rates are all negligible in the time scale of the space program, and the release of entrapped microorganisms by eolian erosion on Mars seems very unlikely.

Survival and Growth of Microorganisms on Mars

The Martian environment is an extremely hostile one by terrestrial standards. The dryness, lack of oxygen, mean low temperature, and high ultraviolet flux make it an inhospitable place for any migrant microorganisms from Earth. It does not follow, however, that Mars is a lifeless planet. Martian conditions are not so severe that they preclude the existence of life forms which, having evolved on the planet, find its climate ideal (*2*). We are concerned here only with the supposition that terrestrial microbes could readily contaminate Mars.

It is assumed in the Sagan-Coleman-COSPAR analysis that the probability P_m that a terrestrial microorganism deposited on the surface of Mars will grow and contaminate the planet is .01—a very high probability. To support this estimate, Sagan and Coleman cite experiments which show that a fraction of the microorganisms present in natural soils—mainly spore-forming anaerobes—survive (but do not grow) during exposure to simulated Martian condition (*32*). This result begs the question of contamination, which requires not just survival but growth over large areas of the planet.

Water, or the lack of it, is the most important factor limiting multiplication of terrestrial forms on Mars (*33*). Optical astronomy has failed to show open bodies of water on the planet (*34*). This agrees with theory, which shows that the pressure of water vapor in the Martian atmosphere is below the triple point. The presence of 10 to 20 microns of precipitable water in the Mars atmosphere (roughly 0.1 percent of that in our atmosphere) was detected by Kaplan *et al.* (*5*) and has been confirmed by Schorn *et al.* (*6*). The latter authors observed temporal and geographic variations in the water-vapor concentration consistent with the hypothesis that water is transported seasonally from one pole to the other. Water vapor was detectable only when it was actually in transit; at other times it was frozen at the winter pole. To quote Schorn *et al.*: "This behavior suggests that Mars is very 'economical' in its use of water, in effect transferring a single pole cap back and forth from one pole to the other." The same concept has been developed by Leighton and Murray (*35*) from considerations of the heat balance of the planet.

It has been suggested that localized geothermal areas on Mars would provide water and higher-than-average temperatures favorable to the survival of indigenous Martian and, presumably, terrestrial life (*36*). Certain rectilinear features discernible in the Mariner 4 photographs may be faults (*37*), and geothermal areas on the earth are often associated with faults. The waters of these fault-associated geothermal areas are surface waters, however, that have penetrated the crust deeply enough to become heated and subsequently have found their way back to the surface along fault fractures. They contain no identifiable juvenile volatiles (*38*). Present evidence casts doubt on the idea that there is any significant amount of geothermal activity on Mars. The aridity and general meagerness of the atmosphere argue against it, as does other evidence suggesting that Mars is an undifferentiated, and therefore internally quiescent, planet. This evidence consists of the lack of a detectable magnetic field and the absence, in the Mariner 4 photographs, of features, such as mountain ranges, reflecting the action of strong internal forces (*39*). Theoretical considerations also support the concept that Mars is an undifferentiated planet (*40*).

By contrast, the earth is a strongly differentiated body with a highly active internal dynamic state. With an area roughly 4 times that of Mars, the earth has produced, by outgassing, an atmosphere 150 times more massive than the Martian one. Yet, at present it is doubtful if more than a fraction of 1 percent of the land surface of the earth is geothermally active.

The extreme dryness of Mars implies that, if liquid water exists at all, it does so only briefly and in small amounts, such as might be produced by the melting of frost after sunrise (*28*). These thin layers of water would soon evaporate, but would linger longest in locales where the dissolution of salts from the soil produced a significant lowering of the vapor pressure. In general, it can be predicted that, if any liquid water persists on Mars, it will be in the form of a saturated solution. This inference suggests that halophilic and osmophilic organisms would have the best chance of surviving on Mars. It is known, however, that these groups of microorganisms have a marked tendency to be aerobic. This is particularly true of the strong halophiles and osmophiles—precisely those organisms which could best cope with the Martian dryness (*41*). Since the Martian atmosphere contains, at most, only traces of oxygen, the likelihood that these organisms could colonize Mars appears to be remote.

The anaerobic condition of Mars can have other, less obvious, implications. In a study of microorganisms in soils collected on the grounds of the Jet Propulsion Laboratory, it was found that some 13 percent grew anaerobically (in a CO_2 atmosphere) on trypticase soy agar at 25°C. No growth of anaerobes occurred, during 2 weeks of observation, in plates subjected to a diurnal freeze-thaw cycle. Under the same temperature conditions, approximately 1 percent of the aerobes produced visible growth (*42*). These results indicate that anaerobes are in the minority in these soils and that they are less able than aerobes to grow under a simulated Martian temperature regime.

Ultraviolet radiation is another hazard awaiting terrestrial migrants to Mars. No gases absorbing in the ultraviolet down to wavelengths of 2400 angstroms have been detected in the Martian atmosphere (*43*). If correct, this finding means that any attenuation in this spectral region is attributable to suspended particulate matter, especially the "blue haze," a phenomenon of the Martian atmosphere that obscures the surface in the blue and violet. The blue haze is variable in time and space: sometimes it covers the entire disk, sometimes it covers only part of the planet, at other times it clears completely (*27*). This implies that the surface of the planet is irradiated, during an unspecified fraction of the Martian year, with essentially unfiltered sunlight in the lethal 2400- to 2800-angstrom range. The integrated solar flux in this spectral range exceeds 20 ergs per square millimeter per second at Mars (*44*). The mean lethal dose for *Micrococcus radiodurans*, an exceptionally radio-resistant bacterium, is 6000 ergs per square millimeter at 2652 angstroms; doubling this dose reduces the survival to less than 0.1 percent (*45*). These doses would be accumulated in a matter of minutes under direct Martian sunlight. Shielded organisms would not be killed, but the ultraviolet flux would be a powerful deterrent to the dissemination of terrestrial microbes through the Martian atmosphere, while the dryness of the soil would prevent their spreading subterraneously.

Summary and Conclusions

The sterility requirements for landed spacecraft tentatively adopted in the COSPAR resolution of 1964 are so severe as to pose a major obstacle to planetary exploration. This by itself would not justify modification of the requirements, since preservation of the biological integrity of Mars is essential for proper exploration of the planet. However, when the physical and biological assumptions underlying the COSPAR recommendations are compared with actual conditions on Mars, as established by recent observations, it becomes apparent that the COSPAR assumptions are unrealistic in important respects. Specifically, the belief that eolian erosion on Mars can effect the release of spores trapped in the interior of solids in periods of time that are short compared with the time scale of the unmanned space program is unsupported by either observation or theory. On the contrary, the analysis suggests that rates of eolian erosion on Mars are very low. Similarly, present knowledge of the Martian environment opposes the view that terrestrial microorganisms would readily contaminate the planet. The combination of dryness, lack of oxygen, and high ultraviolet flux makes the surface of Mars peculiarly unsuitable for the multiplication of terrestrial organisms. Recent studies give little support to the proposal that significant areas of geothermal activity exist on Mars.

These various findings suggest that the COSPAR-recommended constraints could be substantially relaxed without compromising to any significant degree the biological condition of Mars. In particular, a distinction needs to be made between microorganisms trapped in solids and those on exposed surfaces of landed spacecraft. Surface sterility is an unconditional requirement, in the sense that it is imposed by considerations unrelated to the nature of the Martian environment. Sterilization of the interior of solids to the extreme level recommended by COSPAR, however, is based on the assumption that entrapped organisms constitute a substantial hazard to the ecology of Mars. This assumption now seems unjustified, and the need for a high degree of interior sterility is doubtful. Current spacecraft-sterilization policies should be revised accordingly.

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Planetary Contamination II: Soviet and U.S. Practices and Policies

Quarantine can be neither absolute nor unilateral; U.S. policy should acknowledge Soviet practice.

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In the accompanying article (page 1501), Horowitz, Sharp, and R. W. Davies have examined the COSPAR recommendations in the light of new environmental knowledge of the surface of Mars. We now wish to examine the matter from a different point of view: How similar, in fact, are U.S. and Soviet practices and policies? And, what is the likelihood that viable terrestrial microorganisms have already been transported to Venus and Mars as a result of these practices?

We shall show that U.S. and Soviet policies differ completely. The United States continues a strict interpretation of the COSPAR agreement despite past burdens and formidable cost and lead-time implications for its future programs. The Soviets, on the other hand, who attempted entry capsule missions at least 5 years before the United States, have adopted less stringent measures—partial sterilization procedures and modest risk of unintentional impact by other elements of the spacecraft system.

We conclude that Soviet practice has already led to the transfer to Venus, and probably to Mars, of a considerable number of viable terrestrial microorganisms (*1*). Thus, both the COSPAR recommendations and current U.S. planetary quarantine policy should be reviewed and modified to reflect the probability of such transfer.

U.S. Actions and Stated Policies

The NASA planetary quarantine policy became formalized at the end of 1960 and was applied initially to lunar probes. However, technical difficulties with sterilization of the first three Ranger probes launched toward the moon were accompanied, in late 1962, by abandonment of sterilization requirements for the remainder of the Ranger program. Sterilization procedures were also abandoned for the Surveyor lander program, except that "clean room" assembly practices were retained (*2*). These actions were justified on the basis that (i) heat and other kinds of sterilization had resulted in a significant reduction of the reliability of spacecraft, and (ii) the surface environment of the moon was felt to be sufficiently hostile to preclude propagation of any form of terrestrial life.

United States quarantine policy for planetary flyby probes was also modified in late 1962 sufficiently to provide that the probability of landing one or more viable terrestrial microorganisms with either spacecraft or final-stage booster should be less than 10^{-2} for Venus and 10^{-4} for Mars. The application of this quarantine policy to the 1962 Mariner flyby spacecraft launched toward Venus does not appear to have influenced its reliability or its objectives. That spacecraft was not heat-sterilized, nor was the initial aiming point biased away from the planet (*3*).

The Mariner flyby launched toward Mars in November 1964, on the other hand, was initially aimed 600,000 kilometers away from Mars, although the final aiming point was to be only 10,000 kilometers from Mars (*4*). A precise midcourse trajectory correction was then carried out to bring the spacecraft close to the nominal targeting point beside the planet. The a priori calculated probability that this procedure would result in impact on Mars of the unsterilized flyby vehicle was 6.1×10^{-5}, within the 10^{-4} requirement referred to above (*4*). The trajectory requirement placed on the Mariner mission to meet the U.S. interpretation of COSPAR recommendations required additional resources to execute an already high-risk project (*5*). The only future U.S. Mars venture firmly under way at present, the 1969 Mariner flyby, is required to meet the more recent 1966 constraint of a probability of impact of less than 3×10^{-5}.

The quarantine constraint has been set an order of magnitude lower for the 1967 Mariner Venus flyby, a value reflecting the inferred lower probability of contamination of Venus because of anticipated high surface temperatures (*6*). This latest U.S. Venus policy does illustrate that the United States can

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