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COSPAR IDENTIFICATION V.4.3
To be presented at the
XVII COSPAR Meeting, W.G.5D
June 21, 1974
Sao Paulo, Brazil

NASW-2535

New Methodology for Assessing the Probability of Contaminating Mars

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New methodology is proposed to assess the probability that the planet Mars will be contaminated by terrestrial microorganisms aboard a spacecraft. Present NASA methods are based on the Sagan-Coleman formula, which states that the probability of contamination is the product of the expected microbial release and a probability of growth. The proposed new methodology extends the Sagan-Coleman approach to permit utilization of detailed information on microbial characteristics, the lethality of release and transport mechanisms, and of other information about the Martian environment. Three different types of microbial release are distinguished, and for each release mechanism a probability of growth is computed.

Using this new methodology an assessment has been carried out for the 1975 Viking landings on Mars. The resulting probability of contamination for each Viking lander, 6×10^{-6}, is based on expert judgment and is amenable to revision as additional information becomes available.

1. Introduction

The biological contamination of Mars is a complex issue involving a great variety of scientific, engineering, and policy considerations. In many areas the information available is limited. Nonetheless, NASA is committed to a planning process derived from the 1966 COSPAR resolution that is based on assessment of the probability of planetary contamination. The task facing the authors in a recent project for NASA was to criticize the existing assessment methodology, develop appropriate new methodology, and apply the methodology to the 1975 Viking lander.* While the application deserves further review from the scientific community, the results indicate a probability of contamination well below the mission constraint of 10^{-4} imposed by NASA. We believe that the new methodology represents a significant advance over present NASA practice in assessing the probability of planetary contamination.

2. Review of Sagan-Coleman Approach

The probabilistic model of planetary contamination advanced by Sagan and Coleman [2] was the stimulus and theoretical foundation for the 1966 COSPAR resolution. Their procedure used the approximation

$$P(C) = E(N)\, P(G),$$

where

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*A detailed discussion of this research is available in the project final report [1].

C = the event that Mars will be contaminated by terrestrial organisms aboard the spacecraft

N = the number of viable terrestrial organisms (VTOs) released to the Martian environment or into its atmosphere from the spacecraft (a random variable)

$E(N) = \sum_{k=o}^{\infty} k\, P(N=k)$, the expected (or mean) number of VTOs released

G = the event that a single VTO will grow, meaning that it would survive and multiply in the Martian environment.

This formula forms the basis for the assessments of the probability of planetary contamination as they are currently carried out by NASA.

The most serious problem in the use of the Sagan-Coleman formula is that P(G) and E(N) have been used to refer to a randomly selected organism, with no specification of the type of organism or how and where it is introduced into the Martian environment. This approach ignores important available information and places an exceedingly difficult task on the scientific experts who are asked to assign P(G). By a relatively straightforward extension of the Sagan-Coleman approach, the problem can be overcome.

3. <u>Distinguishing among Organisms</u>

To survive and reproduce on Mars a microbe should be facultatively anaerobic, that is, able to reproduce in the absence of oxygen. All terrestrial life requires water in a usable form. Water usable by microbes is unlikely to exist on Mars at temperatures significantly above 0°C, so the microbe should be facultatively psychrophilic, that is, able to reproduce in a temperature range of 0°C or below. For our analysis we assumed that only organisms that are facultatively both anaerobic and psychrophilic contribute significantly to the probability of contamination.*

The UV radiation flux on the Martian surface is strong enough to kill any unprotected terrestrial microorganisms in minutes. A microorganism implanted directly into Martian soil will have a far better chance of surviving than a microbe that rests for many days on the exterior surface of the spacecraft. We therefore distinguished three mechanisms for release of organisms into the Martian environment:

- direct implantation of a microbe into Martian soil
- release by aeolian erosion, presumably during a Martian dust storm, and
- release from the surface of the spacecraft into the Martian atmosphere due to mechanical vibration, thermal effects, or other means.

Dependence on landing site was not included in our analysis, but if future information indicated that the availability of usable water on Mars varies significantly with the release location, the model could be expanded to include this dependence.

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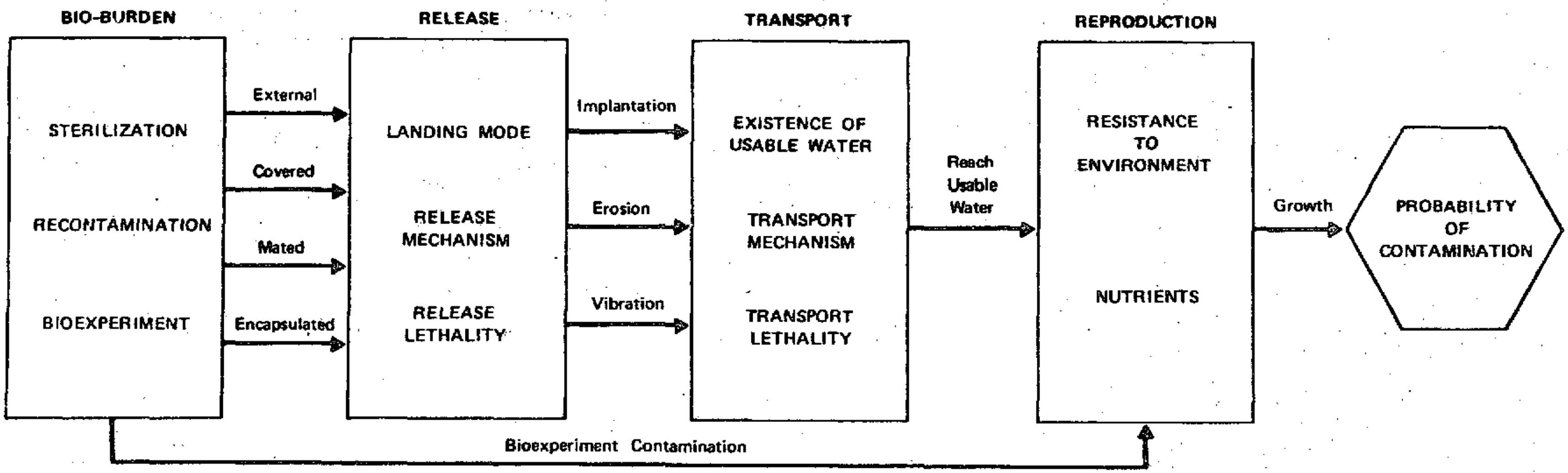
*The importance of organism characteristics was noted six years ago by Sagan, Levinthal, and Lederberg. [3]

4. New Assessment Methodology

An overview of the model for assessing the probability of planetary contamination is shown in Figure 1. The model is composed of four submodels that describe successively (1) the bio-burden on the Viking Lander, (2) microbial release mechanisms, (3) transport in the Martian environment, and (4) the resistance of terrestrial microbes to the Martian environment and the availability of nutrients needed for microbial reproduction on Mars. Communication among the submodels is through the expected number of VTOs that undergo various specific events, such as release from the spacecraft.

The overall output from the model is the expected number of organisms that reproduce on the planet. Contamination is defined as reproduction on the planet by one or more organisms. Since the expected number of organisms that reproduce on the planet is much less than unity, we can interpret this output quantity as the probability of contamination of Mars.

The first submodel provides the subsequent submodels with the number of microorganisms existing on the Viking Lander when it lands on Mars. This biological load is characterized not only by the type of microorganism but also by its location on the lander. Included in this submodel are the number and type of organisms at various locations prior to sterilization, the reduction in bio-burden effected by the sterilization requirements, possible recontamination, and increase or decrease of the microorganism population during transit to Mars. Assessment of the probability of contaminating Mars



Arrows represent transfer of viable terrestrial organisms (VTOs).

FIGURE 1 MISSION CONTAMINATION MODEL

from contamination of the bioexperiments on the lander is calculated directly; the contribution from this term is not significant.

The Release Submodel uses the bio-burden profile as input. It represents explicitly the uncertainty in the landing mode (hard or soft) and the release mechanism: implantation, erosion, or vibration. The lethality of each mechanism is assessed, and the number of VTOs released by each mechanism is calculated.

Unless a microbe from the lander is directly implanted in a hospitable water microenvironment, Martian winds or other transport mechanisms are needed to transport it there. However, the microbe may be killed or immobilized by UV radiation or other causes during transit. These transport and lethality processes have been represented by a dynamic probabilistic model, specifically, a Markov process. Each of the three release mechanisms corresponds to a separate starting state in this process. The output from the Transport Submodel is the expected number of VTOs reaching a microenvironment with usable water.

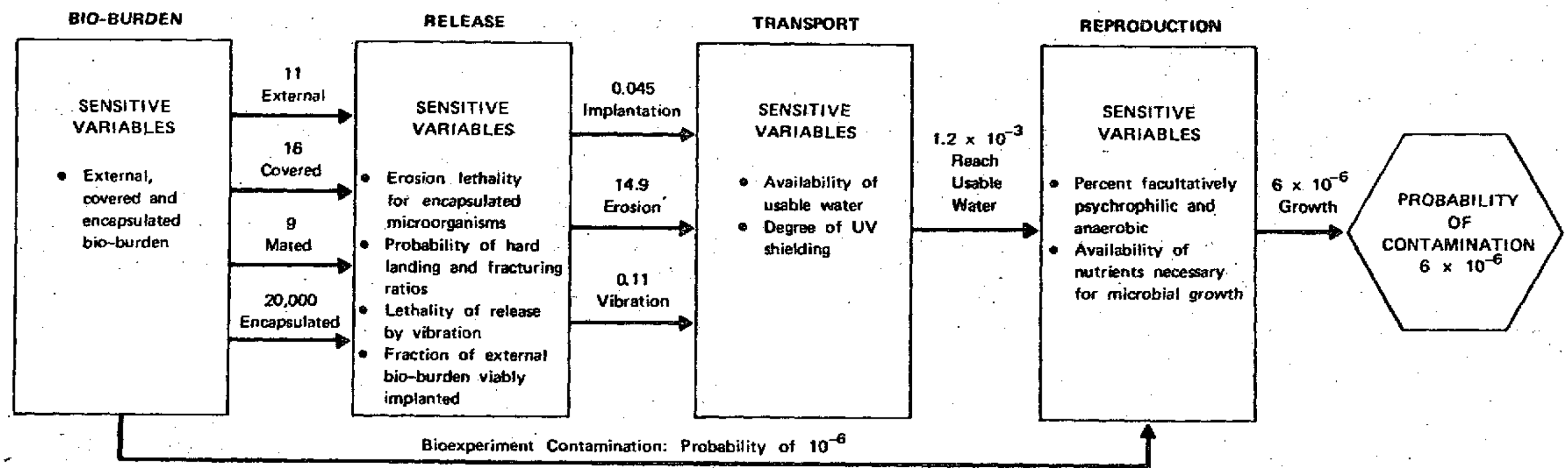
Finally, given that a VTO has reached a hospitable water microenvironment, we examine the circumstances required for its reproduction. The organism must be facultatively anaerobic and able to reproduce at temperatures near or below 0°C. It must also be able to acquire the nutrients necessary for reproduction. The output from the Reproduction Submodel is the number of organisms expected to reproduce in the Martian environment.

5. Results of the Analysis

Given the present state of scientific information, the probability of biological contamination by each of the two Viking landers is 6×10^{-6}. This value is approximately a factor of 16 below the mission constraint of 1×10^{-4} imposed by NASA.

Figure 2, which reproduces the structure of the model presented in Figure 1, indicates the crucial variables and the major intermediate results at each point in the model. The expected number of VTOs transferred from one submodel to the next is indicated on each arrow linking the components. Also, the box representing each submodel contains a list of the critical variables pertaining to that part of the model.

Another important result, not apparent in Figure 2, is that the probability of growth of a microbe varies widely with its release mechanism. A VTO released by implantation is not immediately exposed to the UV radiation and has a probability of growth of 2.8×10^{-5}. At the other extreme, a microbe released by erosion must survive transport in a Martian dust storm and is 100 times less likely to grow and reproduce than a microbe released by implantation; its probability of growth is 2.8×10^{-7}. Microbes released by vibration have an intermediate chance of surviving. Since they were initially located on exposed surfaces and are released in a viable state, they must already be shielded from UV radiation. However, because they fall on surface of the Martian soil, they have less chance of reaching a microenvironment with usable water than do microbes that are implanted directly into the soil. The probability of growth for microbes released by vibration is about 5.3×10^{-6}. These findings clearly



Numbers on arrows give the expected numbers of VTOs.

FIGURE 2 MISSION CONTAMINATION MODEL RESULTS indicate the importance of conditioning the probability of growth on the release mechanism.

6. Insights from Sensitivity Analysis

The above results reflect the present state of scientific information, which is characterized by large uncertainties. The sensitive variables, for which the uncertainty has a significant effect on the probability of contamination, are given in Figure 2.

The probability of contamination is especially sensitive to two characteristics of the transport submodel: the probability of finding water on Mars and the lethality of transport. The two variables of the Reproduction Submodel are also critical. If growth is to occur: (1) the microbe must be resistant to the Martian environment, and (2) it must find appropriate nutrients. Experimentation in microbiological laboratories could address the question of whether different microorganisms surviving the dry heat sterilization cycle could reproduce in a Martian microenvironment if supplied with usable water and UV protection. Unfortunately, little attention has been given to this research until recently [4].

7. Overall Sensitivity to Further Information

To determine the sensitivity of the overall assessment to additional information, an approximate calculation was performed in which 16 of the input variables in the assessment model were considered uncertain. Additional information would cause these inputs to be revised. We modeled the effect of additional information by assigning probabilities to the eventuality that the variables would take on higher or lower values than the nominal values used in arriving at the assessment of 6×10^{-6}. The resulting calculations showed a probability of a few percent that the constraint of 10^{-4} might be violated and a probability of 50 percent that the probability of contamination would be revised to less than 10^{-6} on the basis of the additional information.

8. Conclusion

We have shown how available scientific information can be structured into a model for assessing the probability of contamination. We believe that the use of a formal model as a basis for planning quarantine policy represents a substantial advance over NASA's current approach, which relies on the single parameter P(G). By providing a detailed structural basis for assessing the probability of microbial growth, the model facilitates critical review and revision by the community of scientists concerned with planetary quarantine.

We have recommended to NASA that the current procedure of determining mission sterilization requirements on the basis of a single probability of growth be replaced by a procedure that distinguishes among types of organisms, types of release mechanisms, and other characteristics that affect whether an organism released from a spacecraft will reproduce in the environment of another planet.

Important decisions will be made in the coming years about missions to the outer planets and the return of a surface sample from Mars. It would be highly desirable to have a comprehensive decision framework to address the question of quarantine strategy. The suitability of decision analysis concepts to the quarantine problem has already been pointed out [2]; the methodology and procedures have been applied to similar complex problems in space project planning [5], [6], [7], and other large-scale scientific research programs [8]. The formulation should make explicit the interaction between quarantine procedures and spacecraft cost and reliability, value judgments about microbial proliferation, and the goals of the planetary exploration program.

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ILLUSTRATIONS