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Final Report

ASSESSMENT OF THE PROBABILITY OF CONTAMINATING MARS

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By: BRUCE R. JUDD
D. WARNER NORTH, *Project Leader*
JACQUES P. PEZIER

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ABSTRACT

New methodology is proposed to assess the probability that the planet Mars will be biologically 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 in the model for assessing the probability of contamination. The number of viable microbes released by each mechanism depends on the bio-burden in various locations on the spacecraft and on whether the spacecraft landing is accomplished according to plan. For each of the three release mechanisms a probability of growth is computed, using a model for transport into an environment suited to microbial growth.

This new methodology is used to assess the probability of contamination of Mars by the Project Viking lander. Estimates of the bio-burden provided by Project Viking, recent data on Mars, and recent developments in microbiology have been combined with the judgment of experts in various fields to provide the basis for this assessment. The probability of contamination for each of the 1975 Viking landers has been computed as 6×10^{-6} , which is well below the mission constraint value of 10^{-4} imposed by NASA.

There is currently less confidence in the probabilities input to the model than in the structure of the model itself. Major uncertainties still surround critical factors, like the amount of ultraviolet shielding acquired by microbes and the extent of water and nutrients on Mars. Illustrative calculations give a probability of only a few percent that resolving these uncertainties would cause the probability of contamination to exceed 10^{-4} . On the other hand, these calculations show a 50 percent chance that the probability of contamination would be revised to less than 10^{-6} .

PREFACE

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 COSPAR resolutions that is based on assessment of the probability of planetary contamination. The task facing the authors of this report was the development of new methodology to carry out this assessment.

In applying this methodology to assessment of the contamination probability for the Viking lander, the authors have been fortunate to have the cooperation and assistance of a great many individuals and organizations knowledgeable on the various aspects of this complex issue. Ideally, the inputs and model structure of this report reflect their collective information and judgment. However, the assessment process has been carried out relatively quickly and informally. We have not talked to all experts on each issue, and there are many instances in which experts disagree. For our purpose the disagreement is important only when it leads to different answers to the question, "Does the probability of contamination from the Viking lander exceed the NASA mission constraint?" Our analysis indicates that the constraint is not exceeded. Probability assignments and other inputs in the analysis have been varied over a range judged to represent the change that might occur in these inputs if more information were available. The extensive sensitivity analysis of Section IV shows that the conclusion that the constraint is not exceeded does not change as each input is varied through

its range of values. The assessment process could be refined considerably. More formal procedures could be used to elicit values for the input quantities from which the probability of contamination is calculated, and more detail and structure could be included in the assessment process.

The analysis that has been carried out indicates that the probability of contamination is well below the mission constraint. Therefore, the authors are not recommending that this analysis be refined further at this time. We realize, however, that our conclusions in this respect depend on the information used in the analysis. We hope that the community of scientists concerned with planetary quarantine will give our analysis a careful and critical review, and that they will bring to our attention any points on which the analysis differs with the body of scientific knowledge related to the contamination of Mars.

For reasons set forth in this report the authors believe that the present NASA planning process on planetary quarantine can be improved. The procedures currently being used are based on proposals made a decade ago before any interplanetary exploration had been carried out. We now have much better information about the environments on other planets, and in the next decade we will face a multitude of space exploration decisions in which planetary quarantine considerations will assume great importance.

We believe that the use of formal models for planning quarantine policy represents a substantial advance over NASA's current approach, which relies on a single parameter: the probability of growth. A detailed structural basis for assessing the probability of microbial growth facilitates critical examination and revision in the light of new scientific information.

We recommend that NASA replace the current procedure of determining mission sterilization requirements on the basis of a single parameter, the probability of growth, by a procedure that distinguishes between types of organisms, types of release mechanisms, and other characteristics that affect whether an individual viable terrestrial organism from a spacecraft will reproduce in the environment of another planet.

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Of course, the responsibility for the contents, conclusions, and recommendations of this research report remains with the authors.

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CONTENTS

ABSTRACT iii

PREFACE v

ACKNOWLEDGMENTS ix

LIST OF ILLUSTRATIONS xv

LIST OF TABLES xvii

1 REVIEW AND CRITIQUE OF METHODOLOGY NOW USED TO ASSESS THE
PROBABILITY OF PLANETARY CONTAMINATION 1

1.1 Review of the Sagan-Coleman Approach 1

1.2 Critique of the Sagan-Coleman Formula 2

1.2.1 Definitions of "Growth" and "Contamination" 3

1.2.2 The Approximation of Small Bio-Burden 5

1.2.3 Assumptions of Independence About Microbial
Growth and Release 7

1.2.4 Failure to Distinguish Among Microorganisms
in Assessing P(G) 10

1.3 Rationale for Amendments to the Sagan-Coleman Approach 10

1.3.1 Organism Characteristics 10

1.3.2 Release Mechanism 12

1.3.3 Landing Site 12

1.4 An Extension of the Sagan-Coleman Formula 12

1.4.1 Type of Organism 13

1.4.2 Release Mechanisms 13

1.5 The Assessment of Small Probabilities 14

1.5.1 Reference Events 14

1.5.2 Modeling and Decomposing Complex Events 15

1.5.3 Assessing the Probability of Microbial
Growth and Contamination 15

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1.6	Difficulties Arising from the Decision Context	16
1.6.1	Meeting the NASA Mission Constraint	17
1.6.2	Implicit Value Judgments	17
1.7	The Advisability of a Decision Analysis of Quarantine Strategy	18
2	SUMMARY OF NEW METHODOLOGY AND FINDINGS	21
2.1	The Mission Contamination Model	21
2.1.1	Bio-Burden Submodel	24
2.1.2	Release Submodel	24
2.1.3	Transport Submodel	25
2.1.4	Reproduction Submodel	25
2.2	Results of the Analysis	26
2.3	Identification of Crucial Variables	28
2.3.1	Bio-Burden Submodel Variables	31
2.3.2	Release Submodel Variables	31
2.3.3	Transport Submodel Variables	31
2.3.4	Reproduction Submodel Variables	32
2.4	Simplified Version of the Calculations	33
2.5	Comparisons with the Woods Hole Assessment of P(G)	37
3	THE MODEL FOR ASSESSING THE PROBABILITY OF CONTAMINATION OF MARS	39
3.1	The Bio-Burden Submodel	39
3.1.1	Bio-Burden Submodel Parameters	40
3.1.1.1	Sensitivity of Microorganisms to Dry Heat Sterilization	41
3.1.1.2	Recontamination	45
3.1.1.3	Contamination of the Bioexperiment	46
3.1.1.4	Increase or Decrease of Microbe Population During Flight	47
3.1.2	Bio-Burden Submodel Summary	47
3.2	The Release Submodel	47
3.2.1	Release Submodel Parameters	47
3.2.2	Release Submodel Structure	50
3.2.3	Release Submodel Summary	54

3.3	The Transport Submodel	59
3.3.1	Markovian Models	59
3.3.1.1	A Three-State Model	61
3.3.1.2	A Five-State Model	62
3.3.2	The Transport Submodel: A Six-State Markov Model	64
3.3.3	Transport Submodel Parameters	69
3.3.3.1	Definitions of the Six States	69
3.3.3.2	Transition Descriptions and Probabilities	70
3.3.3.3	Microbe Starting States	72
3.3.4	Transport Submodel Results and Sensitivity Analysis	73
3.3.4.1	Direct Inspection of the Transport Submodel	73
3.3.4.2	Markov Model Computations	77
3.3.5	Transport Submodel Summary	81
3.4	The Reproduction Submodel	83
3.4.1	Reproduction Submodel Parameters	83
3.4.1.1	Resistance to Environment	83
3.4.1.2	Availability of Nutrients	85
3.4.2	Reproduction Submodel Summary	86
4	SENSITIVITY ANALYSIS	87
4.1	Model Structure and Sensitivity Analysis Methodology	88
4.2	Submodel Transfer Functions	90
4.3	Sensitivity Analysis of Submodels	91
4.3.1	Release Submodel	93
4.3.1.1	Marginal Sensitivity Analysis	95
4.3.1.2	Joint Sensitivity Analysis	96
4.3.2	Transport Submodel	99
4.3.2.1	Marginal Sensitivity Analysis	99
4.3.2.2	Joint Sensitivity Analysis	101

4.4	Identification of Variables Most Crucial to the Probability of Contamination	101
4.5	Simulation of the Effect of Additional Information . . .	106
5	RESULTS, RATIONALE FOR NEW METHODOLOGY, AND A RECOMMENDATION	111
5.1	Results of the Analysis	111
5.2	Rationale for New Methodology	112
5.3	Recommendation	112
APPENDICES		
A	THE SAGAN-COLEMAN FORMULA--SUMMARY AND EXCERPTS FROM A PREVIOUS SRI REPORT	117
B	RELEASE SUBMODEL PROBABILITY ASSIGNMENTS	133
C	TRANSPORT SUBMODEL PROBABILITY ASSIGNMENTS	141
	REFERENCES	153

DD FORM 1473

ILLUSTRATIONS

1.1	Comparison of Linear Approximation (Eq. 1.1) and Exact Computation (Eq. 1.3) of the Probability of Contamination for $P(G) = 10^{-6}$	7
2.1	Mission Contamination Model	22
2.2	Mission Contamination Model Results	27
2.3	Approximate Version of the Transport Submodel	36
3.1	The Bio-Burden Submodel	40
3.2	Decrease in Microbe Population with Dry Heat Sterilization Time	42
3.3	Effect of Recontamination on Expected Bio-Burden	45
3.4	The Release Submodel	48
3.5	Tree Structure for VTO Release	51
3.6	Release Submodel Parameters	55
3.7	Tree Structure for VTO Release: Parameters	56
3.8	The Transport Submodel	60
3.9	Three-State Representation of Microbial Transport	61
3.10	Five-State Representation of Microbial Transport	63
3.11	Five-State Representation of Dust Storm Cycle	65
3.12	Transport Markov Model	66
3.13	Transport Markov Model--Dust Storm Cycle	68
3.14	Transport Markov Model: Probability Assignments	71
3.15	Transport Submodel Showing the Probability That a VTO Will Occupy Each State of the Transport Submodel During the Course of One Dust Storm Cycle	74
3.16	Approximate Version of the Transport Submodel	76
3.17	Three-State Reduced Process Showing Transition Probabilities and Starting State Occupancies	79

3.18	The Reproduction Submodel	84
3.19	Reproduction Submodel Calculations	85
4.1	Relative Contributions to the Probability of Contamination	92
4.2	$P(C)^*$, Probability of Contamination Given Further Information	109
A.1	Basic Logical Structure of the Sagan-Coleman Model	120
A.2	Basic Logical Structure of the Proposed Model	120
A.3	Distribution Implying Independent Trials	124
A.4	Distribution Implying Perfectly Dependent Trials	124
A.5	Uniform Distribution	124
A.6	Probability of All Tails Versus Number of Trials	126
A.7	Illustrative Probability Distribution for Fraction of Organisms Achieving Growth	128
A.8	Discrete Approximation for Growth Distribution	128
B.1	Tree for VTO Release: Parameters	134
B.2	Release Submodel Parameters	135
C.1	Transport Markov Model: Probability Assignments	142

TABLES

2.1	Nomenclature of Contamination Submodel Variables	29
2.2	Contamination Model: Marginal Sensitivity Analysis	30
3.1	Bio-Burden Submodel Parameters	44
3.2	Release Submodel Matrix: Probability that a single VTO in the given location will be released by each of the mechanisms	58
3.3	Transport Submodel Summary	82
4.1	Release Submodel Marginal Sensitivities	94
4.2	Most Critical Pair of Parameters in the Release Submodel	97
4.3	Most Critical Pairs of Parameters and Triplet in the Release Submodel	98
4.4	Transport Submodel Marginal Sensitivities	100
4.5	Transport Submodel Joint Sensitivities	102
4.6	Contamination Model: Marginal Sensitivity Analysis	103
4.7	Three Series of Informational Changes Causing the Probability of Contamination to Exceed 10^{-4}	105
C.1	Fraction of Spores Surviving 2×10^3 erg/sec/cm ² Flux	143
C.2	Fraction of UV Flux Transmitted to the Surface as a Function of Dust Storm Optical Thickness	143
C.3	Fraction of Spores Surviving Attenuated UV Flux	144
C.4	Water Existence Mechanisms	147

1 REVIEW AND CRITIQUE OF METHODOLOGY NOW USED
TO ASSESS THE PROBABILITY OF PLANETARY CONTAMINATION

1.1 Review of the Sagan-Coleman Approach

During the early 1960s, concern about biological contamination led to international agreement that suitable quarantine procedures would be employed on spacecraft sent to other planets. Attention was focused on the planet Mars because it was judged that Mars might be capable of supporting terrestrial microorganisms. In 1966 the Committee on Space Research (COSPAR) of the International Council of Scientific Unions adopted a resolution that spacefaring nations conduct their unmanned exploration of Mars in such a way that the total probability of contamination during a specified quarantine period not exceed 10^{-3} . The probabilistic model of planetary contamination advanced by Sagan and Coleman¹ was the stimulus and theoretical foundation for this COSPAR resolution and the basis for NASA's current planning procedures for planetary quarantine.

The main problem Sagan and Coleman addressed was calculating a probability of contamination $[P(C)]$ of Mars for various possible sequences of unmanned missions during the quarantine period. They also addressed the question of how the probability of contamination for an individual mission could be computed. Their procedure, stated without detailed justification, was to use the approximation

$$P(C) = E(N) P(G) \quad , \quad (1.1)$$

where

C - the event that Mars will be biologically 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)

$$E(N) = \sum_{k=0}^{\infty} k P(N=k)$$

= the expected (or mean) number of VTOs released

G = the event that a single VTO will grow, meaning that it would survive, multiply, and contaminate a significant fraction of the planet.

We shall refer to Eq. (1.1) as the Sagan-Coleman formula. It forms the underlying basis for the assessments of the probability of planetary contamination as they are currently carried out by NASA in the planning of all unmanned missions outside the earth-moon system.

The research task undertaken by the Decision Analysis Group of Stanford Research Institute for the Planetary Quarantine Officer of NASA has been to reexamine the appropriateness of the Sagan-Coleman formula as a basis for NASA planning. The initial contract was to carry out a detailed critique of the Sagan-Coleman formula.² The second contract, reported herein, has been to develop new methodology appropriate for assessing the probability of biological contamination and to apply this methodology to the Project Viking Mars lander. For the convenience of the reader, the earlier research is summarized below and in Appendix A.

1.2 Critique of the Sagan-Coleman Formula

Sagan and Coleman examined the problem of planetary contamination a decade ago. Their formulation is an approximation that may have been adequate considering the knowledge available in 1965, but that is no

longer adequate considering the much more extensive knowledge available today. Possible problems inherent in using the Sagan-Coleman formulation as a basis for planning lie in the following areas:

- (1) The definition of "growth" and "contamination".
- (2) The approximation of small bio-burden.
- (3) The assumptions of independence about microbial growth and release.
- (4) The failure to distinguish among different types of microorganisms in the assessing the probability of growth $[P(G)]$.

Problems arising in the first three areas are not particularly serious and are easily remedied. The fourth difficulty, failure to distinguish among microorganisms in assessing $P(G)$, may be overcome by extending the Sagan-Coleman formula to apply separately to different classes of organisms. This approach is the basis for the new methodology described in this report.

The assessment of small probabilities is generally a difficult task. The complex economic, technological, and policy issues surrounding space exploration greatly increase the difficulty of obtaining accurate, unbiased assessments of the probability of planetary contamination. A more comprehensive formulation would include the effect of the decision context on the probability assessment process. The advisability of a reformulation is discussed at the end of this section, but the accomplishment of the reformulation is outside the scope of this report.

1.2.1 Definitions of "Growth" and "Contamination"

The first difficulty with the Sagan-Coleman paper and the COSPAR resolution is a question of definition. What is meant by growth, and what is meant by contamination? The Sagan-Coleman paper is not very explicit in defining these terms:

... the landing of unsterilized space vehicles on Mars may obscure subsequent attempts to detect in a pristine state indigenous life on that planet. To avoid possible biological contamination of Mars, it is clear that entry vehicles should be carefully and conscientiously sterilized.¹

The 1964 and 1966 COSPAR resolutions were no more explicit in defining "contamination." The term has been defined in the planetary quarantine literature, but not very precisely. The following definition represents one of the most precise in the planetary quarantine literature:

A planet will be considered to have been contaminated if one or more microorganisms of terrestrial origin are deposited on its surface or into its atmosphere and then grow and spread so as to bias future biological exploration over a specified period of time.³

The vagueness of the definition was perhaps reasonable in view of the stringent requirements that COSPAR was considering at the time. The 1964 COSPAR resolution stated:

The probability that a single viable organism be aboard any spacecraft intended for planetary landing must be less than 1×10^{-4} ... [and] ... the probability limit for accidental planetary impact by an unsterilized flyby or orbiter must be less than 3×10^{-5} during the interval terminating at the end of the initial period of planetary exploration by landing vehicles (approximately one decade).¹

By limiting to 10^{-4} the probability that even one viable terrestrial organism would reach the environment of another planet, the COSPAR resolution effectively set that same number as the upper limit for the probability that the planet would be contaminated. The details of how a viable microbe aboard a spacecraft might affect Mars are not so significant if we assess as less than 1 in 10,000 the chance that a viable microbe will in fact reach the planet. However, when we realize that the Viking landers are presently assumed to have on board on the order of 2×10^4 viable microbes, it is apparent that the situation has

changed dramatically. The need for a more precise definition of contamination assumes greater importance.

In our analysis we have not attempted to resolve what is meant by such phrases as "grow and spread," or "contamination of a significant fraction of the planet." Instead we have chosen to avoid the definitional difficulty by assigning "growth" and "contamination" definitions that are more restrictive but less ambiguous than the previous usage. Throughout this report "growth" will mean that a VTO has replicated itself in the Martian environment, using nutrients obtained from Mars rather than from the spacecraft. "Contamination" will mean that growth has occurred within the quarantine period. (Notice that contamination of Project Viking biology experiments does not necessarily fall within our definitions. We do not count as contamination the reproduction of VTOs using nutrients obtained on board the spacecraft.) Our definitions are more restrictive than previous usage, for no matter what amount of growth is taken to imply "contamination of the planet," the process must begin with a single reproduction. Given that a single reproduction does occur, it seems reasonable to assume that the probability of subsequent reproductions is on the order of unity. Rather than attempt to determine how many subsequent reproductions are necessary for "significant" contamination, we would prefer to see consideration given to a general reformulation of the planetary quarantine problem.

1.2.2 The Approximation of Small Bio-Burden

The Sagan-Coleman formula (1.1) is an approximation based on a Bernoulli model for the growth of individual microbes.³ Contamination occurs if one or more microbes grow; therefore the event that contamination does not occur implies that none of the microbes that are viably released reproduce:

$$1 - P(C) = \sum_{k=0}^{\infty} P(N = k) [1 - P(G)]^k \quad . \quad (1.2)$$

We expand $[1 - P(G)]^k$ as a power series, and if $k P(G) \ll 1$ for all values $N = k$ of significant probability, we can drop all but first-order terms in $k P(G)$ and we obtain the formula (1.1):

$$P(C) = E(N) P(G) \quad .$$

To see the implications of this approximation, consider the case where the probability of growth, $P(G)$, is 10^{-6} and the number of microbes released, N is 10^7 . Naive use of Eq. (1.1) leads to a probability of 10, which is clearly in error since probabilities are defined to lie in the range from zero to 1. If Eq. (1.2) is used to calculate the probability of contamination, the results are:

$$P(C) = 1 - [1 - P(G)]^N \quad (1.3)$$

$$= 1 - 4 \times 10^{-5} \quad . \quad (1.4)$$

Figure 1.1 shows how $P(C)$ varies with N over the range $N = 10^5$ to $N = 10^7$.

The probability of contamination remains linear in N , the number of organisms released, as long as N is much smaller than $1/P(G)$, the reciprocal of the probability of growth. If the probability of release of a number of organisms comparable to $1/P(G)$ is very small, Eq. (1.1) will be an excellent approximation of Eq. (1.2). The approximation is conservative in that Eq. (1.1) will give a higher value for the probability of contamination than Eq. (1.2).

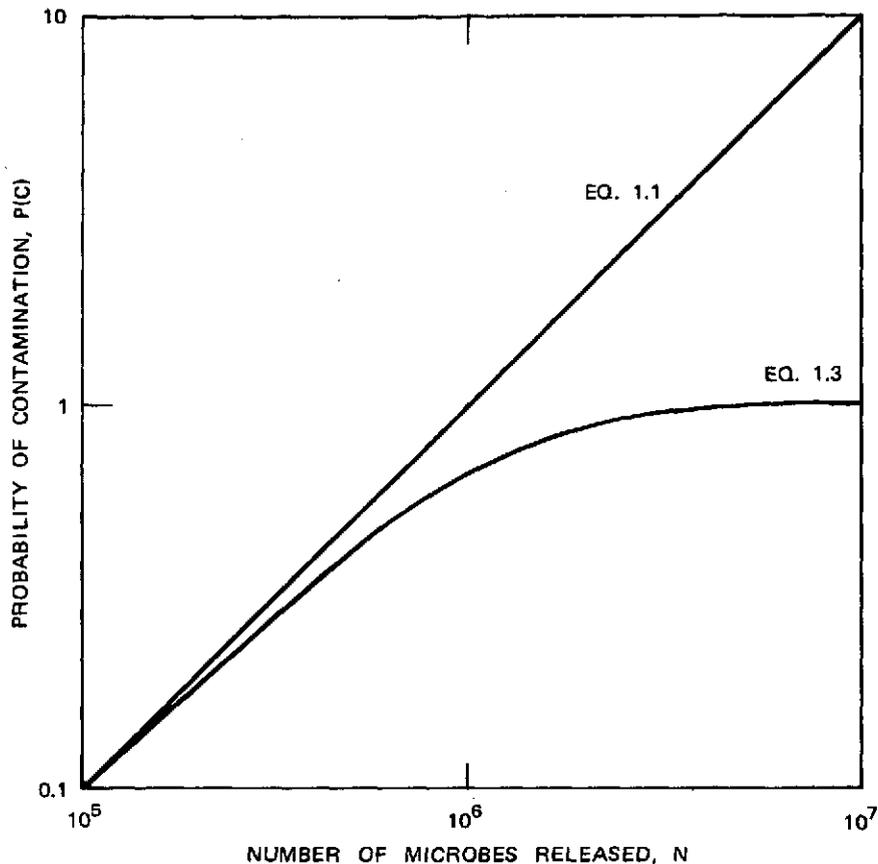


FIGURE 1.1 COMPARISON OF LINEAR APPROXIMATION (EQ. 1.1) AND EXACT COMPUTATION (EQ. 1.3) OF THE PROBABILITY OF CONTAMINATION FOR $P(G) = 10^{-6}$

1.2.3 Assumptions of Independence About Microbial Growth and Release

Equation (1.3) shows how $P(C)$ depends on N . If $P(G) = 10^{-6}$ and $N = 10^5$, we find $P(C) = 0.0955 \cong 0.10$. If $N = 10^7$, then $P(C) = 1 - 4 \times 10^{-5} = 0.99996$. This result occurs without the approximation of small bio-burden by which Eq. (1.1) is derived from Eq. (1.2). The result implies that for a release of 10^7 organisms, contamination is a virtual certainty. On the basis of this probability, a reasonable man should be willing to bet at odds of 1,000 to 1 that contamination of Mars will occur if 10^7 microorganisms are released onto Mars. However, if only 10^5 microorganisms are released, the probability of contamination is less than 10 percent.

This conclusion, which is based on the Bernoulli trials model implicitly underlying the Sagan-Coleman formula, is not consistent with the present state of scientific information about Mars. Most experts would not conclude that contamination of Mars is a near certainty, no matter how many viable terrestrial microorganisms are released. For example, there may be no water on Mars in a form usable by any microbes to accomplish reproduction. Because we are uncertain about Martian environmental factors, such as the existence of usable water, we are uncertain about $P(G)$. This uncertainty conflicts with independence assumptions in the model underlying Eq. (1.2).

Our first report² dealt largely with the independence assumptions that underlie the Sagan-Coleman formula. The assumption of the Bernoulli trials model--that release and the growth, given release, of individual microbes are independent events--is not necessary. A more general formulation is possible, which leads to a nonlinear relation between the expected number of VTOs released, $E(N)$, and the probability of contamination, $P(C)$. This formulation is discussed in Appendix A, which summarizes the earlier report.

Relaxation of the independence assumption leads to a considerable increase in the difficulty of the assessment process. Assessments of the following form must be obtained: If a large number VTOs (e.g., 10^9) were released into the Martian environment, what is the probability that at least 0.001 percent of them (e.g., 1 part in 10^5) would survive and result in growth? Figure A.8 in Appendix A shows a probability distribution constructed from judgments of this type.

If the number of released organisms is small compared with the reciprocal of the probability of growth, the error introduced by assuming independence among surviving individual microbes is small. This error is conservative in the sense that the effect of the independence

assumption is to overstate the probability of contamination. The independence assumptions lead to the unwarranted conclusion that contamination is nearly certain only when the number of microbes released exceeds the reciprocal of $P(G)$ by at least 1 order of magnitude (Eq. (1.4)). Except for the possibility of contamination in the bioexperiment, such high levels of microbial release are not judged possible. Therefore, the error introduced by assuming independence is not significant in our analysis. The assumption of independence among microbial survival events has been maintained.

A more serious problem inherent in the Sagan-Coleman formula is the assumption of independence between the number of microbes released and the event that a microbe survives. Other factors enter into determining the likelihood of growth or release. For example, the type of landing made by a spacecraft can have a significant effect on both the number of VTOs released and their subsequent survival rate. A hard landing by the spacecraft can result in much larger microbial release than a soft landing. A hard landing also makes growth more likely, because microbes are implanted directly in Martian soil without significant exposure to ultraviolet (UV) radiation. The analytical methodology described below rectified this shortcoming of the Sagan-Coleman approach by explicitly including in the model the dependence of the microbial release mechanism on the type of landing.

Contamination of the biology experiment may result in release levels large enough so that the errors stemming from the independence assumption and the approximation of small bio-burden become substantial. As a result, contamination of the biology experiment will be handled in a special manner in our analysis. However, using the probability currently assigned to bioexperiment contamination, this term does not contribute significantly to the overall probability of planetary contamination.

1.2.4 Failure to Distinguish Among Microorganisms in Assessing P(G)

The most serious problem in the use of the Sagan-Coleman formula is its aggregation of the types of microorganisms, of the mechanisms by which microbes would be released in a viable condition into the Martian environment, and of the locations on Mars in which the microbes might be deposited. P(G) and E(N) have been used by the planetary quarantine community 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). Furthermore, by a relatively straightforward extension of the Sagan-Coleman approach, the problem can be circumvented. The remainder of the report presents a refined methodology for assessing P(G).

1.3 Rational for Amendments to the Sagan-Coleman Approach

The Sagan-Coleman approach can be extended to include explicitly information on organism characteristics, release mechanism, and landing site. We now review the reasons why the extensions are important.

1.3.1 Organism Characteristics

All microbes on a spacecraft are not identical. The microbes deserving serious concern are those capable of adapting to the extremely hostile environment on Mars. What characteristics must a microbe have to survive and reproduce on Mars? Since Mars has little or no free oxygen, the microbe should be facultatively anaerobic, that is, able to reproduce in the absence of oxygen. All terrestrial life requires water and must be able to obtain it in a liquid or otherwise usable form. The extremely low temperatures and pressures on Mars make the existence of

liquid phase water extremely improbable. If usable water does exist, it is likely to be in the form of concentrated salt solutions or melting ice trapped under dust. Because water usable by microbes is unlikely to exist at temperatures significantly above 0°C, the microbe should be facultatively psychrophilic, that is, able to reproduce in a temperature range of 0°C or below.

The first amendment to the Sagan-Coleman approach should be to specify that we are concerned not so much with the total population of microbes on the spacecraft as with the subpopulation of microbes that are both facultative anaerobes and facultative psychrophiles. Furthermore, since the Viking lander will receive terminal dry heat sterilization, it is virtually certain that all surviving organisms on the spacecraft will be spores. A small fraction of the naturally occurring spore population seems to be extremely resistant to dry heat sterilization.

How large is the subpopulation of VTOs in the spacecraft bio-burden that is facultatively both anaerobic and psychrophilic? This question can be addressed by experimentation in terrestrial microbiology laboratories, but it has received virtually no attention until recently.* Our estimate that 5 percent of the spacecraft bio-burden is facultatively both psychrophilic and anaerobic is based on judgment rather than on experimental data. It is hoped that current experimental programs will provide a better estimate of this quantity in the near future.†

* The importance of organism characteristics was noted six years ago by Sagan, Levinthal, and Lederberg.⁴

† Preliminary results from this research are discussed in subsection 3.4.

1.3.2 Release Mechanism

A second needed amendment to the Sagan-Coleman approach is to specify the means by which the microbe is released into the Martian environment. The UV radiation flux on the Martian surface is strong enough to kill any unprotected terrestrial microorganisms in a matter of minutes. A microorganism implanted directly into Martian soil will therefore have a much better chance of surviving than a microbe that rests for many days on the exterior surface of the spacecraft.

1.3.3 Landing Site

As we suggested in our earlier report,² the location of the spacecraft landing might be another characteristic to be taken into account in modifying the Sagan-Coleman formula. If it is judged that the probability of a microbe reaching usable water is highly dependent on the location where the microbe is released, then the probability of growth should be assessed also on the basis of the spacecraft landing site. However, planetwide dust storms could conceivably transport a microbe from the spacecraft to any point on the surface of the planet. Our assessments correspond to the general mid-latitude location of the Viking 1975 landing sites. If further information indicates that liquid water on Mars is found only in a small region of the planet's surface, the model could be expanded to include more precisely the dependence on landing site.

1.4 An Extension of the Sagan-Coleman Formula

One approach in assessing the probability of contamination will be to use an expanded version of the Sagan-Coleman formula:¹

$$P(C) = \sum_{i,k} P_{i,k} (G) E(N_{i,k}) \quad , \quad (1.4)$$

where the index k refers to the type of organism and the index i refers to the way in which the microbe is released into the Martian environment.

1.4.1 Type of Organism

For our analysis we have distinguished two types of organisms:

$k = 1$, organisms that are facultatively both anaerobic and psychrophilic

$k = 2$, all other organisms.

We shall assume that the probability of growth for organisms that are not facultatively both anaerobic and psychrophilic is on the order of 10^{-9} or below. Based on this assumption, we can conclude that these other organisms do not contribute significantly to the probability of planetary contamination. We shall therefore drop the subscript k and concern ourselves only with $k = 1$.

1.4.2 Release Mechanisms

We have distinguished three mechanisms for release of organisms into the Martian environment:

$i = 1$, direct implantation of a microbe into Martian soil

$i = 2$, release by aeolian erosion, presumably during a Martian dust storm, and

$i = 3$, release from the surface of the spacecraft into the Martian atmosphere due to mechanical vibration, thermal effects, or any other means.

By defining category $i = 3$ to include all other mechanisms for viable microbe release, we have thereby established a mutually exclusive and collectively exhaustive set of release mechanisms. Our task now becomes one of assessing the probability of growth, $P_i(G)$, and expected number of microbes released, $E(N_i)$, for the three different categories.

1.5 The Assessment of Small Probabilities

The assessment of probabilities on the order of 0.001 or less is at best a difficult task.* The problem is that when asked to assess probabilities smaller than, say, 1/100, we all have difficulty conjuring up familiar reference events that we perceive to be of comparable likelihood. In many applications a probability of 10^{-2} or 10^{-3} can in fact be used as a working definition of impossibility. It might be argued that scientists are more comfortable than most people in working with numbers as small as 10^{-3} ; however, we are not convinced that even they are accustomed to using numbers of this magnitude to summarize their judgment about complex, unlikely events.

1.5.1 Reference Events

Providing a set of familiar reference events against which relative likelihood can be compared is one way an analyst can aid in the task of assessing the likelihood of rare events. For example, if a person says that he assesses the probability of Event E_1 to be 10^{-4} and the probability of Event E_2 to be 10^{-6} , we can be quite sure that he considers both events unlikely, and E_1 more likely than E_2 . Experience indicates, however, that caution should be used in attaching any absolute significance to the numerical assessments. Would this same person, for example, rather bet on Event E_2 occurring or on being dealt a royal flush in a game of five-card stud poker? Since calculation will show that the probability of being dealt a royal flush in that situation is about

* There is a large literature on probability assessment, but very little of it is addressed to assessing the probability of rare events.^{5,6,7} The SRI Decision Analysis Group is preparing a research memorandum describing methodology for assessing small probabilities. This memorandum will be available in the summer of 1974.

1.5×10^{-6} , the person's assessment of the probability of Event E_2 as 10^{-6} would lead to the logical conclusion that he would prefer to bet on the royal flush. Nevertheless, if the question of preference were asked directly ("Would you rather bet on Event E_2 occurring or on the possibility of being dealt a royal flush?"), he might answer that he prefers to bet on E_2 . This would mean that he had in effect revised his assessment of the probability of E_2 .

1.5.2 Modeling and Decomposing Complex Events

Rare events can frequently be broken down into a sequence of required component events. It is often useful to enrich the model structure to include the sequence and then encode the conditional probability of each event, given the occurrence of its predecessors. By using this procedure we enable the expert to assess only probabilities of a readily comprehensible magnitude.

1.5.3 Assessing the Probability of Microbial Growth and Contamination

We will use this modeling approach to assess $P_i(G)$ and therefore $P(C)$. For microbial growth to occur, the following sequence of events is required:

- (1) Usable water must exist on Mars.
- (2) The microbe must reach this usable water in a viable condition.
- (3) The nutrients required for microbial reproduction must exist at the site of the usable water.

We will assess probabilities for each event and use them to develop the probability of growth and then the overall probability of contamination.

This modeling approach is similar to the process used to arrive at the assessment of $P(G)$ of 10^{-6} for Mars, currently being used

by NASA.⁸ A conference of scientists meeting at Woods Hole in July 1970 assessed P(G) by considering the fraction of terrestrial microbes that might be suited to the Martian environment, the probability that usable water and other nutrients would be present on Mars, and the probability that "sufficient" numbers of viable terrestrial microorganisms could reach these locations to cause contamination.^{9,10,11} Unfortunately, the assumptions, definitions, and probability computations used in this assessment were never formally documented so that they could be checked and revised as further information became available. Furthermore, the value of $P(G) = 10^{-6}$ was established as a compromise between the even-odds (median) estimate of 3×10^{-9} and the maximum estimate of 1×10^{-4} , which was the parameter value actually recommended to NASA by the Review Group.¹¹ The setting of $P(G) = 10^{-6}$ was to a large extent an arbitrary choice, and the determination of this parameter has remained a source of uneasiness within the planetary quarantine community.

1.6 Difficulties Arising from the Decision Context

The difficulties experienced at the Woods Hole Conference highlight a basic problem in the Sagan-Coleman formulation of the planetary contamination problem. The formulation fails to distinguish value judgments about contamination from judgments on the likelihood that this event will occur. Various reasons have been given for concern over contamination: the loss of scientific data on indigenous Martian life, a moral obligation to protect indigenous life from potentially hostile terrestrial organisms, possible effects on the potential for reengineering the planet, and so forth.^{1,3,4,12,13} Scientists who believe that the biological contamination of Mars could be a major catastrophe for the human race will argue for a more conservative assessment of P(G), while scientists who envision contamination in less dramatic terms will argue that the zealous attention given to planetary quarantine considerations imposes

unwarranted costs and reliability penalties on space missions to Mars. The 1966 COSPAR resolution reflects a compromise between these viewpoints. Placing an upper limit of 10^{-3} on the probability of "significant" contamination during the period of unmanned exploration was agreed on as an acceptable way to include quarantine considerations in the planning of Mars missions.

1.6.1 Meeting the NASA Mission Constraint

In accordance with the 1966 COSPAR resolution, NASA has established a mission constraint for Project Viking that the maximum limit of the estimated probability that each flight of the specified mission will result in microbial contamination is 1×10^{-4} .⁸ Having based our analysis on improved assessment measures and the most recent information available to us, we conclude that this mission constraint would not be violated. To put this conclusion in perspective, we considered whether additional information might lead to a revision of the assessed probability of contamination that would be sufficient to cause a violation of the NASA mission constraint. On the basis of approximate calculations, it appears that the probability of additional information causing the contamination probability to be revised to a value above 10^{-4} is on the order of a few percent.

1.6.2 Implicit Value Judgments

The value judgments on contamination that are implicit in the COSPAR resolution remain a source of concern. Some scientists have argued for a conservative assessment of the probability of contamination; this approach immediately raises the question of how much conservatism is enough.^{9,11,14} We believe that a much better approach is to make explicit the value judgments about microbial proliferation on Mars and

its relation to the goals of a Mars exploration program. The existence of indigenous life on Mars should have an important bearing on the importance of contamination by terrestrial organisms. Suppose, for example that it could be determined that Mars has no indigenous life but that its geological, chemical, and physical characteristics provide a strong incentive for continued unmanned exploration of the planet. Should this exploration be carried out under the present 10^{-3} COSPAR constraint, with its implicit penalties in cost and reliability, or should the constraint be relaxed? Or suppose that Mars were known to have simple indigenous life forms of a type that is easily metabolized by terrestrial organisms. What implications would this information have for the planning of future unmanned exploration? Should much more stringent sterilization requirements be placed on space missions to Mars, given this new set of conditions? The planning approach embodied in the 1966 COSPAR resolution lacks flexibility to reexamine the consequences of microbial proliferation as more is learned about the Martian environment. A broader approach should be taken to enable planning on quarantine strategy to be more responsive to the state of scientific knowledge and the concerns of the scientific community.

1.7 The Advisability of a Decision Analysis of Quarantine Strategy

It would be highly desirable to have a decision framework to address the question of quarantine strategy. Important decisions will be taken in the coming years about missions to the outer planets and the return of a soil sample from Mars. The suitability of decision analysis concepts to the quarantine problem has already been pointed out;⁴ the methodology and procedures have been applied to similar complex problems in space project planning^{14,15,16} and other large-scale scientific research programs.¹⁸ A decision analysis reformulation would make explicit the meaning of the term "contamination." This definition would be

structured so that it could be responsive to new information accumulated in the course of ongoing space exploration. For example, knowledge about the existence and types of indigenous life on Mars could be taken into account in determining what probability of contamination should be considered acceptable in missions to the planet. The analysis would also make explicit the interaction between quarantine procedures and spacecraft cost and reliability.

2 SUMMARY OF NEW METHODOLOGY AND FINDINGS

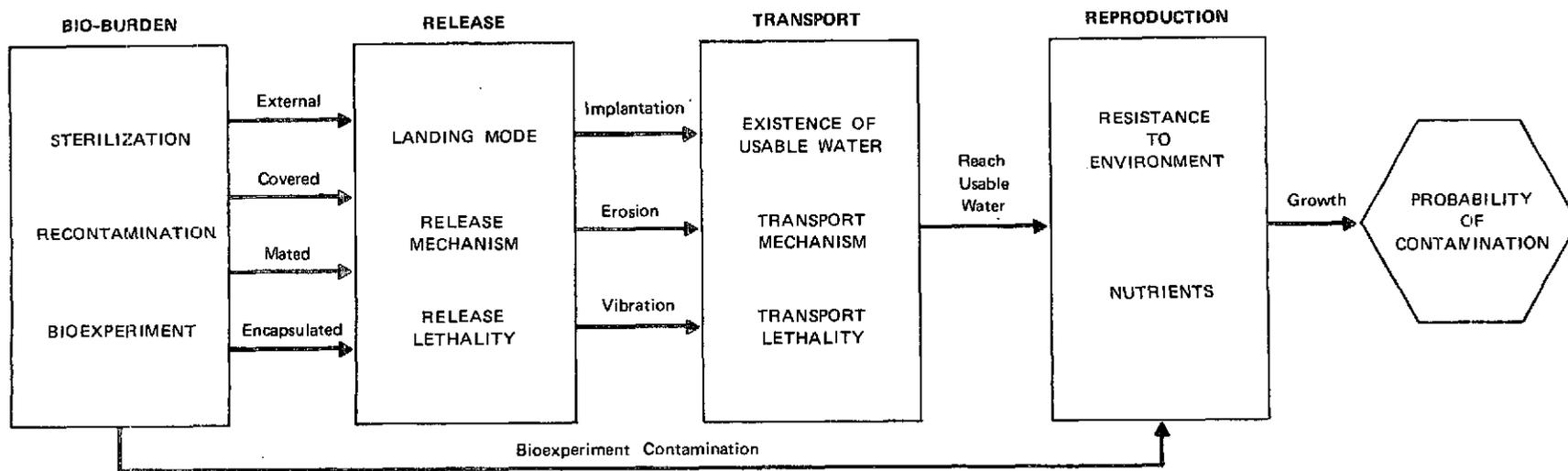
This section presents a brief overview of the model developed to assess the probability of contamination resulting from a specific space mission, such as the Project Viking lander. The relation between the methodology described here and current NASA procedures for assessing the probability of contamination should be readily apparent; we shall clarify those points that are not obvious. A summary of findings follows discussion of the model.

2.1 The Mission Contamination Model

An overview of the model for assessing the probability of planetary contamination is shown in Figure 2.1. The model is composed of four components or 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 a set of intermediate variables that describe 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. Reproduction on the planet by one or more organisms is regarded as implying contamination. 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.

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Arrows represent transfer of viable terrestrial organisms (VTOs).

FIGURE 2.1 MISSION CONTAMINATION MODEL

Before describing these submodels in detail, we shall describe their relationship to the Sagan-Coleman formula: $P(C) = E(N) P(G)$. The first two submodels allow a determination of the expected number of VTOs released in each of three fashions. These quantities correspond to the microbial release term $E(N)$ in the Sagan-Coleman formula. Our formulation differs from current NASA procedure in that we distinguish three possible fashions in which a microbe may be viably released; this is done for four categories of microbe location on the spacecraft. Present NASA procedures give a single probability of release for each location category; our methodology uses three.

The last two submodels address the question of whether a VTO that has been released into the Martian environment (in one of three fashions) will survive and reproduce. These two submodels correspond to the term $P(G)$ in the Sagan-Coleman formula. Again, the procedure differs from standard NASA procedures in that three different types of release are distinguished.

In addition, release of a large quantity of microbes because of contamination of the bioexperiment is considered in a separate calculation. Because the quantity of VTOs released would be large, the approximation of small bio-burden needed for the Sagan-Coleman formula would not hold. However, if contamination did occur, it is reasonable to assume that all organisms would be of the same type. Therefore, the upper bound on the contribution of bioexperiment contamination to planetary contamination can be computed as the probability of bioexperiment contamination times the probability that the organisms will be facultatively both psychrophilic and anaerobic. Using this calculation, we can show that the contribution from bioexperiment contamination is negligible compared with other sources for planetary contamination. We shall now consider the four submodels.

2.1.1 Bio-Burden Submodel

The first submodel is intended to provide the subsequent analysis with the number of microorganisms existing on the Viking lander when it lands on the planet Mars. This biological load is characterized not only by the type of microorganism but also by its location on the lander. Four location types are considered:

- External surface.
- Covered surface (the interior surface of a container).
- Mated surface (contact surface between two parts of the spacecraft).
- Encapsulated in solid materials.

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. The outputs from the Bio-Burden Submodel are the number, type, and location of microorganisms on the lander when it lands on Mars.

(Note: Detailed versions of bio-burden submodels have been developed and continuously revised under the supervision of the Viking Project team. Although we have carried out some investigation of these issues on our own, we have used in our analysis a set of numbers developed by the Viking Project team.¹⁹)

2.1.2 Release Submodel

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. Three release mechanisms are considered:

- Implantation (organisms put in direct contact with the ground by the lander, e.g., on the landing pads).

- Aeolian erosion.
- Vibration (organisms falling off the lander because of mechanical operations, thermal effects, and the like).

The lethality of these mechanisms and the number of microbes exposed to them are considered. The output from the Release Submodel is the number of VTOs released by each mechanism. The release mechanism is important because it influences the lethality of the subsequent transport process. Specifically, the amount of UV radiation received by a microbe is assumed to depend on its release mechanism.

2.1.3 Transport Submodel

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, since a microbe will be exposed to high levels of UV radiation during transport, it may be killed or immobilized before reaching a water microenvironment. These transport and lethality processes have been represented by a dynamic probabilistic model, specifically, a six-state Markov process. Each of the three release mechanisms corresponds to a separate starting state in this process. The probability of a microbe reaching a hospitable water microenvironment has been assigned, using a side calculation based on the two most likely hypotheses for the existence of usable water. The output from the Transport Submodel is the expected number of VTOs reaching a microenvironment with usable water.

2.1.4 Reproduction Submodel

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, resistant to the

extreme low temperatures in the Martian diurnal cycle, and able to reproduce at temperatures near or below 0°C. It must also be able to acquire the nutrients necessary for microbial reproduction. The output from the Reproduction Submodel is the number of organisms expected to grow and reproduce in the Martian environment.

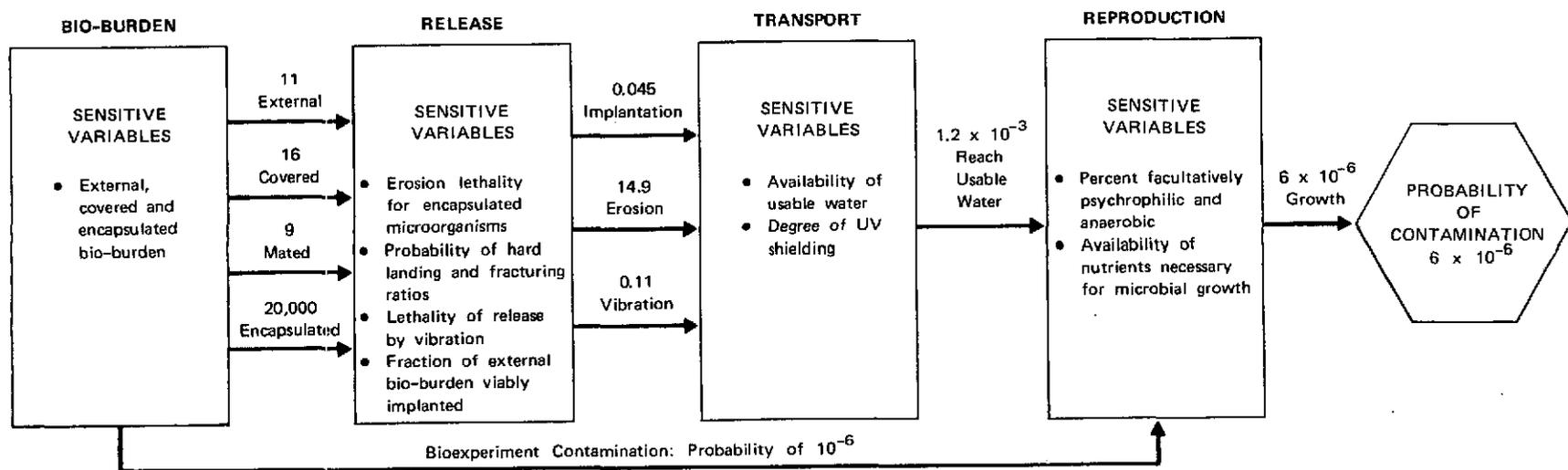
The complete Mission Contamination Model permits the probability of contamination to be expressed as a function of the relevant input variables in the four submodels. It represents the application of a general methodology to the evaluation of the risk of contamination. Conclusions from the model, which are reported in detail in Sections 4 and 5, are summarized in the following subsection.

2.2 Results of the Analysis

Application of the new methodology that we have described shows that, 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 imposed by NASA.

Figure 2.2, which reproduces the structure of the model presented in Figure 2.1, 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 this part of the model.

Before we discuss in more detail the major sources of uncertainty in the model, another important result, not apparent in Figure 2.2, must be given: 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 radiations and has a probability of growth



Numbers on arrows give the expected numbers of VTOs.

FIGURE 2.2 MISSION CONTAMINATION MODEL RESULTS

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 radiations. However, because they fall on the surface of the Martian soil, they have less chance of reaching a microenvironment with usable water than 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 indicate the importance of conditioning the probability of growth on the release mechanism.

2.3 Identification of Crucial Variables

The above results, of course, reflect the present state of scientific information, which is characterized by large uncertainties. Critical variables are those where the uncertainty has a significant effect on the probability of contamination. These variables are listed and described in Table 2.1.

For ease of reference, the model variables will often be designated in this report by the short definition or the four character symbol shown in Table 2.1. Columns 2, 3, and 4, of Table 2.2 represent low, nominal, and high values for each variable. No exact probabilistic definition has been given for the low and high values, but they may be viewed as representing approximately 5 and 95 percentiles. The last two columns of Table 2.2 represent low and high values of the probability of contamination when each of the 13 variables in the table is given its low and high values and other variables are held constant at their nominal values.

Table 2.1

NOMENCLATURE OF CONTAMINATION SUBMODEL VARIABLES

Main Symbol	Variable Name	Alternate Symbols	Nominal Value	Definition
Bio-burden Submodel				
1bio	External	b_1	11	Output variables--expected number of VTOs on lander in each of four location types: External surfaces Covered surfaces Mated surfaces Encapsulated in solid materials
2bio	Covered	b_2	16	
3bio	Mated	b_3	9	
4bio	Encapsulated	b_4	20,000	
Release Submodel				
1rel	{ Hard landing } *		0.002	State variables { Probability of a hard landing
2rel	{ Newly hard landing; } † { exposed covered or mated }	a, f_{ne}	0.1	{ Probability that an organism on a covered or mated surface will be newly exposed on hard landing
3rel	{ Newly hard landing; } { exposed encapsulated }	a, f_{ne}	0.001	{ Probability that an encapsulated organism will be newly exposed on hard landing
4rel	{ Implanted soft landing }		0.001	{ Probability that an organism located on an external surface will be implanted on soft landing
5rel	{ Implanted hard landing }	b	0.5	{ Probability that an organism located on an external surface or newly exposed will be implanted on hard landing
6rel	{ VTO vibration }	c	0.01	{ Probability that a VTO on an external surface or newly exposed will survive release by vibration
7rel	{ VTO erosion; covered }	d	0.8	{ Probability that a VTO on a covered surface will survive release by erosion
8rel	{ VTO erosion; mated }	d	0.01	{ Probability that a VTO on a mated surface will survive release by erosion
9rel	{ VTO erosion; encapsulated }	d	0.0001	{ Probability that a VTO encapsulated in a solid material will survive release by erosion
10rel	Implantation	I	0.45	Output variables--expected number of VTOs released in a viable state by each of three mechanisms: Implantation Erosion Vibration
11rel	Erosion	E	14.89	
12rel	Vibration	V	0.11	
Transport Submodel				
1tra	{ Survive transit }	P_1	0.01	State variables { Probability that a VTO will survive transportation by a Martian dust storm
2tra	{ Find water }	P_6	0.005	{ Probability that a VTO will reach a microenvironment with usable water after transportation by a dust storm
3tra	{ Find lodging }	P_4	0.5	{ Probability that a VTO will be lodged with UV shielding after transportation by a dust storm
4tra	{ Water deposition }	P_{11}	0.0005	{ Probability that water will be deposited on a VTO lodged with shield during a dust storm cycle
5tra	{ Swept aloft }	P_{12}	0.5	{ Probability that a VTO lodged with shield in a dry location will be swept aloft by the next dust storm
6tra	{ Death while lodged }	P_8	0.001	{ Probability that a VTO lodged with shield will be killed otherwise than by UV radiation during a dust storm cycle
Reproduction Submodel				
1rep	{ Facultative psychrophiles } { and anaerobes }	f	0.05	State variables { Probability that an organism on the spacecraft will be capable of surviving and reproducing in Martian microenvironments with usable water, nutrients, and UV shielding (i.e., will be facultatively both psychrophilic and anaerobic)
2rep	{ Nutrients }	n	0.1	{ Probability that the nutrients necessary to support microbial growth will be present in a Martian microenvironment with usable water

* {A} indicates the probability assigned to Event A.

† {A|B} indicates the probability assigned to Event A, given the occurrence of Event B.

Table 2.2

CONTAMINATION MODEL: MARGINAL SENSITIVITY ANALYSIS

Contamination Model Variables				Probability of Contamination	
Parameters Being Varied	Values			(Units are 10 ⁻⁶ ; Nominal = 5.9)	
	Low	Nominal	High	Low	High
Bio-burden Submodel Variables					
1bio External	2.2	11	55	5.0	10.7
2bio Covered	3.2	16	80	3.1	20.2
4bio Encapsulated	4,000	20,000	100,000	5.0	10.4
Release Submodel Variables					
1rel {Hard landing }	0.0004	0.002	0.01	5.2	9.6
3rel {Newly hard landing; exposed encapsulated }	0.0001	0.001	0.01	5.4	10.9
4rel {Implanted soft landing }	0.0001	0.001	0.01	5.7	8.7
6rel {VTO vibration }	0.001	0.01	0.1	5.4	11.1
9rel {VTO erosion; encapsulated }	0.00001	0.0001	0.001	5.4	10.9
Transport Submodel Variables					
1tra {Survive transit } (P ₁)	0.001	0.01	0.1	2.2	45.2
2tra {Find water } (P ₆)	0.0005	0.005	0.05	1.5	49.9
4tra {Water deposition } (P ₁₁)	0.00005	0.0005	0.005	5.0	15.2
Reproduction Submodel Variables					
1rep {Facultative psychrophiles and anaerobes }	0.005	0.05	0.25	0.6	29.6
2rep {Nutrients }	0.01	0.1	0.5	0.6	29.6

Low and high values of the probability of contamination correspond to the low and high values of the variables.

2.3.1 Bio-Burden Submodel Variables

Considering first the bio-burden variables, we can observe that microbes on covered surfaces play a predominant role. An increase of their population by a factor of 5 is reflected by an increase of the probability of contamination by a factor of 3.5. The reason for this large effect is that microbes on covered surfaces have a good chance of being released in a viable state. They may be viewed as located in a box, a corner of which is eroded away. A fraction of the interior surface will be exposed to lethal UV radiation, but many microbes will still be shielded from UV radiation prior to being swept out of the box by Martian winds. Equally interesting to note is that microbes on mated surfaces do not appear in the list of critical variables. In fact, their contribution to the probability of contamination is only on the order of 1 percent.

2.3.2 Release Submodel Variables

Several Release Submodel variables are important but none seem to be highly critical. It is unlikely that receiving perfect information about any one variable could increase the probability of contamination by more than a factor of 2.

2.3.3 Transport Submodel Variables

The probability of contamination is much more sensitive to two characteristics of the transport submodel. Foremost is the probability of finding water on Mars. Several models have been proposed for the existence of water in a form usable by terrestrial microorganisms.*

* See, for example, Refs. 20 and 21.

The probability of the existence of these models and the fraction of the Martian surface on which they might operate has been quantified. As a result, a probability of 5×10^{-3} has been assigned to the event that an organism deposited at random on the Martian surface will find usable water. A number 10 times smaller would reduce the probability of contamination by a factor of 4, and a number 10 times larger would multiply the risk of contamination by a factor of 8. Alternate mechanisms have also been considered by which water might be deposited on VTOs lodged in initially dry locations in the course of the 50-year quarantine period.

Almost equally important is the lethality of transportation by Martian dust storms. As stated earlier, the majority of VTOs that may cause contamination are released by aeolian erosion. They may be swept aloft in a dust storm or simply saltate on the Martian surface. In both cases they are exposed to high levels of UV radiation. In fact, unless the microbe lives in a colony or is attached to a particle that offers UV shielding, it should most certainly be killed after a few minutes of exposure. We have assigned a probability of 0.01 to the event that a microbe will find sufficient UV shielding to survive transportation by a dust storm. This value is supported by experimental results²² showing a two-order of magnitude decrease in populations of *B. Cereus* and *B. Subtilis* airborne in simulated Martian dust clouds over a period of weeks.

2.3.4 Reproduction Submodel Variables

Finally, the importance of the two variables of the Reproduction Submodel is clearly apparent. The two variables correspond to two conditions that must be met if growth is to occur: (1) the microbe must be resistant to the Martian environment, and (2) it must find appropriate nutrients.

Experimentation in microbiology 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 that problem until recently. Based on informal discussions with several experts, a probability of 5 percent has been assigned to reproduction under these conditions. However, further information might very well decrease this number by one or two orders of magnitude. Such a decrease would cause exactly the same relative reduction of the risk of contamination. Likewise, a change in the probability of finding nutrients, currently set at 10 percent, would cause the same relative change in the probability of contamination.

2.4 Simplified Version of the Calculations

Section 3 contains the development of our assessment model for the contamination of Mars and Section 4 is devoted to detailed sensitivity analyses on the assumptions and parameters used in the model. As a consequence we can show that the main results can be derived from a very simplified model. We will describe this approximate approach here because it brings into focus the major aspects of a very complex situation, but it should be remembered that the analyses of Sections 3 and 4 were necessary to draw this simple picture.

The approximate assessment of the risk of contamination can be performed in two steps:

- (1) Calculation of the number of VTOs released by each of the three release mechanisms: implantation, erosion and vibration.
- (2) Estimation of the probability of growth following these releases.

The expected number of released VTOs is estimated as follows.

- (1) The implantation mechanism operates essentially on VTOs on external surfaces and encapsulated in solid materials. The following breakdown shows three dominant possibilities contributing to a total of 0.045 VTOs released by implantation:

<u>Number of VTOs per Location Type</u>	X	<u>Probability of Landing Mode</u>	X	<u>Other Release Parameters (see Table 2.1)</u>	=	<u>Expected Number of VTOs Released by Implantation</u>
External 11	X	Hard landing 0.002	X	(5rel) 0.5	=	0.011
External 11	X	Soft landing 0.998	X	(4rel) 0.001	=	0.011
Encapsulated 20,000	X	Hard landing 0.002	X	(3rel)(5rel) 0.001 X 0.5	=	0.020
Others						<u>0.003</u>
Total						0.045

- (2) The expected number of VTOs released by erosion is 14.89 and consists essentially of VTOs on covered surfaces and encapsulated:

<u>Erosion Type and Number of VTOs Released</u>	X	<u>Probability of Type of Landing</u>	X	<u>Other Release Parameters (see Table 2.1)</u>	=	<u>Expected Number of VTOs Released by Erosion</u>
Covered 16	X	Soft landing 0.998	X	(7rel) 0.8	=	12.80
Encapsulated 20,000	X	Soft landing 0.998	X	(9rel) 0.0001	=	2.00
Other						<u>0.09</u>
Total						14.89

(3) The vibration release mechanism contributes a total expected number of 0.11 VTOs. Practically all were located on external surfaces and are released by vibration following a soft landing:

<u>Location Type and Number of VTOs Released</u>	<u>×</u>	<u>Probability of Type of Landing</u>	<u>×</u>	<u>Other Release Parameters (see Table 2.1)</u>	<u>=</u>	<u>Expected Number of VTOs Released by Vibration</u>
External 11	×	Soft landing 0.998	×	(6rel) 0.01	=	0.11

Figure 2.3 is an approximate representation of the ways in which a released VTO can be viably transported to a microenvironment with usable water. (See Table 2.1 for an exact definition of the parameters.) The numbers associated with each of the arrows indicate the probability that the microbe will be viably transported from one state to another. Using the probabilities expressed in Figure 2.3, we can make the following calculations:

<u>VTO Release Mechanism</u>	<u>Transport Variables (see Table 2.1)</u>	<u>=</u>	<u>Probability of an Organism Reaching Usable Water in a Viable State</u>
Implantation	$(2tra) + (3tra) \times (2 \times 4tra)$ 0.005 + 0.5 × 0.001	=	5.5×10^{-3}
Erosion	$(1tra) \times [(2tra) + (3tra) \times (2 \times 4tra)]$ 0.01 × (0.005 + 0.5 × 0.001)	=	5.5×10^{-5}
Vibration	$2 \times (4tra)$ 0.001	=	1×10^{-3}

The total expected number of VTOs reaching water is therefore:

Implantation	$0.045 \times 5.5 \times 10^{-3}$	=	2.5×10^{-4}
Erosion	$14.89 \times 5.5 \times 10^{-5}$	=	8.2×10^{-4}
Vibration	0.11×10^{-3}	=	1.1×10^{-4}
Total		=	11.8×10^{-4}

Each organism has a 5 percent chance of being resistant to the Martian environment and a 10 percent chance of finding appropriate nutrients to grow and proliferate. The probability of contamination of Mars is therefore:

$$11.8 \times 10^{-4} \times 0.05 \times 0.1 = 6 \times 10^{-6}$$

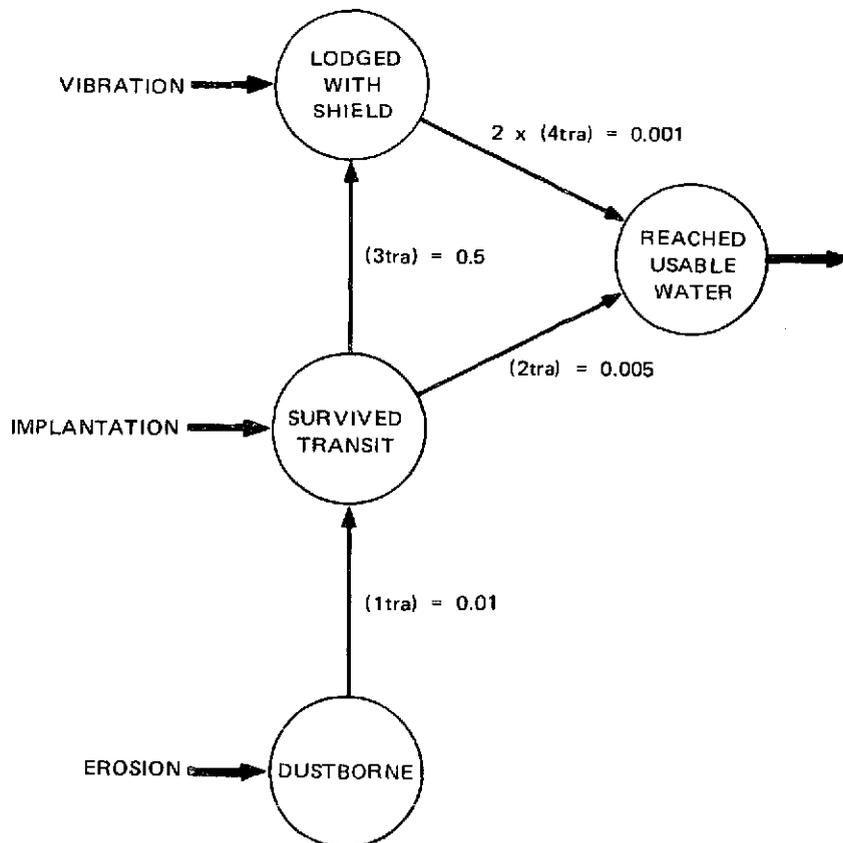


FIGURE 2.3 APPROXIMATE VERSION OF THE TRANSPORT SUBMODEL

Approximate calculations have been carried out to evaluate the overall uncertainty associated with the 6×10^{-6} probability of contamination estimate. The results show 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 additional information.

2.5 Comparisons with the Woods Hole Assessment of P(G)

At a meeting in Woods Hole, Massachusetts, in July 1970, planetologists and microbiologists combined their expertise to estimate the probability of growth of a terrestrial microorganism deposited on the surface of Mars. This probability of growth, P_g , was considered as the product of three factors defined as follows:

- P_{me} = the probability that there exist microenvironments (ME) on Mars that would support growth of the most hardy terrestrial organisms (HTO)
- P_{hto} = the probability that an HTO capable of growing in the defined microenvironment exists among the organisms present in and on the spacecraft
- P_t = the probability that such an HTO on release from the spacecraft will be transported to a microenvironment and survive the trip.

Estimates for these three parameters were as follows:¹¹

	<u>Even-Odds Estimate</u>	<u>0.999 Confidence Factor-- Upper Limit Estimate</u>
P_{me}	1×10^{-2}	1
P_{hto}	3×10^{-4}	1×10^{-2}
P_t	1×10^{-3}	1×10^{-2}
$P_g \leq P_{me} \cdot P_{hto} \cdot P_t$	3×10^{-9}	1×10^{-4}

The conclusion was to recommend the value of $P_g = 1 \times 10^{-4}$ and to point out at the same time the conservative nature of this estimate.

The following comparisons can be made with the parameters of our model:

- (1) The probability of existence of a suitable microenvironment (P_{me}) is comparable to the probability of finding water and nutrients, that is $(5 \times 10^{-3})(0.1) = 5 \times 10^{-4}$, or 20 times less than the even-odds (median) estimate of P_{me} .
- (2) The probability that a VTO on the spacecraft will be suited to the Martian microenvironment (P_{hto}) should be compared with our 5 percent assessment for the fraction of psychrophiles and anaerobes. Partly because of a difference in the definition of a suitable microenvironment, the two assessments are quite different.
- (3) The transport probability P_t is especially difficult to compare with any one parameter in our model. For organisms released by erosion we have adopted approximately 10^{-2} , but the probability of surviving transport is almost 1.0 for VTOs directly implanted in the ground.

As stated earlier, our estimates of the probabilities of growth conditional on the release mechanisms are:

<u>VTO Release Method</u>	<u>Probability of Growth</u>
Implantation	2.8×10^{-5}
Erosion	2.8×10^{-7}
Vibration	5.3×10^{-6}

These are the numbers that should be compared with the Woods Hole recommendation of 1×10^{-4} and the NASA specification of 10^{-6} for P_g .

3 THE MODEL FOR ASSESSING THE PROBABILITY OF CONTAMINATION OF MARS

The Mission Contamination Model is composed of four submodels, each describing a necessary step in the contamination process:

- Bio-Burden by location on the spacecraft.
- Release of microbes into the Martian environment.
- Transport to a microenvironment in which the microbe can find water in a form usable for reproduction.
- Reproduction by microbes in a hospitable water microenvironment, given that necessary nutrients are available and that the microbe is of a type suited to the conditions that prevail in the microenvironment.

Communication between one submodel and the next is through the expected number of VTOs reaching one stage and going on into the next stage in the contamination process. The emergence of one or more VTOs from the output of the reproduction model is considered contamination. The probability of contamination can be taken to be the expected number of VTOs in the output of the reproduction model since this number is much smaller than unity.

We shall now discuss each submodel and the scientific knowledge that each of them summarizes.

3.1 The Bio-Burden Submodel

The Viking bio-burden submodel is used to determine the expected number of VTOs in each of four location types on the lander: external surface, covered surface (the interior surface of a container), mated surface (contact surface between two parts), and encapsulated in solid materials. Figure 3.1 shows the inputs to this submodel.

3.1.1 Bio-Burden Submodel Parameters

The first input is the expected number of VTOs on the spacecraft in each of the four locations prior to sterilization. A second input is the sensitivity of various types of organisms to sterilization. The third is the effect of the sterilization regime on microbial population. The fourth input treats the possible recontamination after terminal sterilization and the fifth input deals with in-flight increase or reduction of the bio-burden. As shown in Figure 3.1, the output of the Bio-Burden Submodel is the expected number of VTOs found in each of the four locations: external, covered, mated, and encapsulated.

The following major input parameters are described below:

- (1) the sensitivity of microorganisms to dry heat sterilization,
- (2) recontamination,
- (3) contamination of the bioexperiment, and
- (4) increase or decrease of the microbe population during flight.

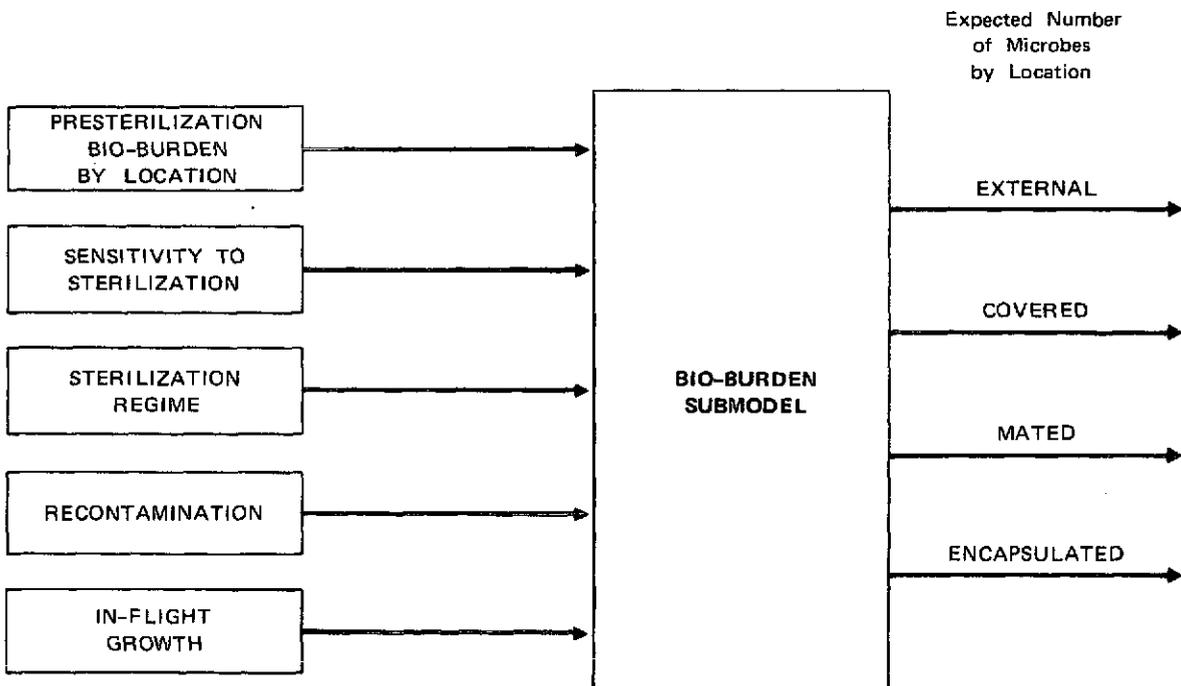


FIGURE 3.1 THE BIO-BURDEN SUBMODEL

3.1.1.1 Sensitivity of Microorganisms to Dry Heat Sterilization

Empirical evidence^{23, 24, 25} suggests that the reduction in microbe population over time during dry heat sterilization can be characterized by a curve like that shown in Figure 3.2. The abscissa represents time on a linear scale, and the ordinate represents the number of spores plotted on a log scale. (The numbers in Figure 3.2 are illustrative only and are not intended to be an accurate representation of empirical results.) A linear fit to the curve in Figure 3.2 has generally been employed as an approximation:

$$N_1 = N_0 \times 10^{-t/D} ,$$

where:

N_0 = initial population

N_1 = poststerilization population

t = sterilization time

D-value = the time required for 1 order of magnitude reduction in microbe population.

Recent evidence has indicated that the "fit" may be poor; a small subpopulation of the organisms has been found to be much more resistant to dry heat sterilization. Thus, it has been suggested²⁶ that a piecewise linear fit be made to the asymptotes of this curve. Using this piecewise linear approximation, we arrive at two exponential functions that characterize population reduction over time from the heat sterilization. The time required for 1 order of magnitude reduction in microbe population at a given temperature is termed "D-value" (decimal reduction time). Denoting by primes and double primes the normal and hardy subpopulations, we arrive at the following relationship between the initial population N_0 and the population N_1 of viable organisms after a sterilization time t:

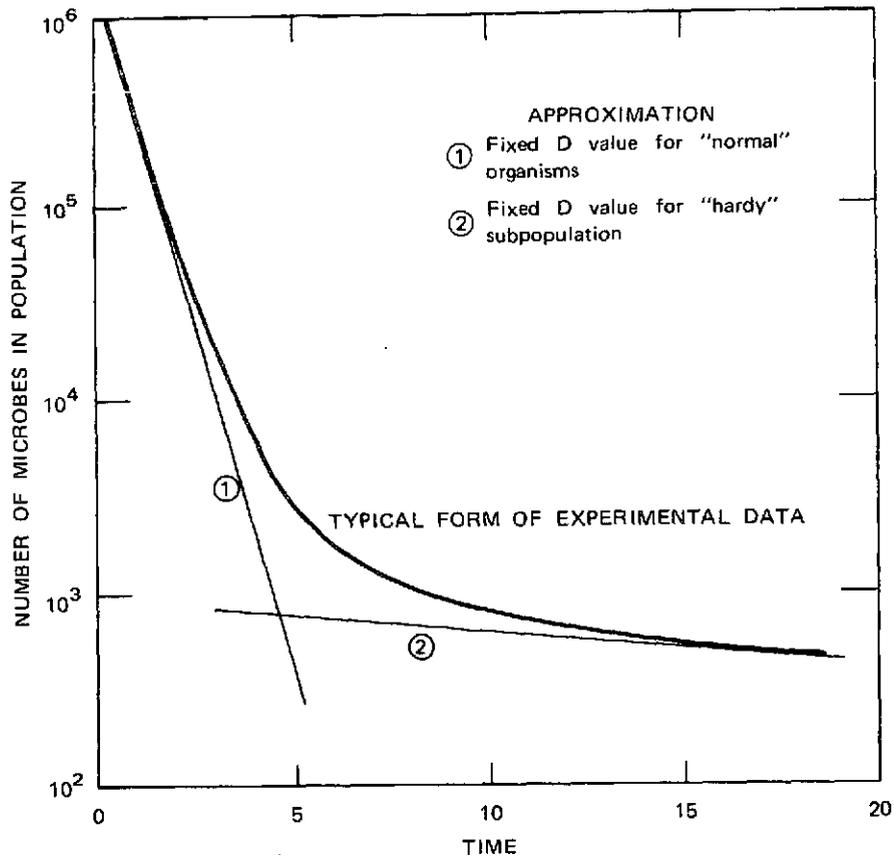


FIGURE 3.2 DECREASE IN MICROBE POPULATION WITH DRY HEAT STERILIZATION TIME

$$N_1 = N'_0 10^{-t/D'} + N''_0 10^{-t/D''} \quad , \quad (3.1)$$

with

$$N_0 = N'_0 + N''_0 \quad .$$

The nominal (normal subpopulation) D-values now being used for Project Viking^{8, 27} are 0.5 hour for external and covered organisms, 1 hour for mated organisms, and 5 hours for encapsulated organisms at 125°C. However, since the current sterilization regime specifies approximately 113°C for 30 hours, new D-values must be computed for each of the surfaces. D-values vary exponentially as a function of temperature. The exponential rate of change is usually referred to as the Z-value. The number currently used for this Z-value^{8, 28} is 1 order

of magnitude increase in D-value per 21°C decrease in sterilization temperature. The equation:

$$D_{113} = D_{125} 10^{(125-113)/21} \quad (3.2)$$

is used to compute D-values for the 113°C regime. The "D-Value" column in Table 3.1 gives the current D-values for both the normal and the hardy organisms (normal on the left; hardy on the right).

Table 3.1 also contains the current numbers for the pre- and post-sterilization bio-burdens with the number of normal organisms given on the left and hardy organisms given on the right for each location. The number of hardy organisms is computed by multiplying the nominal bio-burden by 0.0025.²⁹ The third column of numbers is computed using Eq. (3.1) with the appropriate D-values from Column 2. Note that for external, covered, and mated organisms the computed post-sterilization bio-burden is exceedingly low. However, the number of hardy organisms is in the range of 1 to 10. For the encapsulated organisms, the poststerilization bio-burden of nominal microbes is at least an order of magnitude greater than that for hardy organisms. The fourth column gives the Project Viking estimate of the bio-burden at each of the four locations. There are several inconsistencies between the estimates and our calculations of the burden. However, based on the computed numbers, the Project Viking estimates can be considered conservative; as best we can determine, they overstate the expected population.

The encapsulated burden was extrapolated from experiments in which plastics or ceramics similar to those used on the lander were ground up and then assayed to determine bio-burden. The extrapolation resulted in an expected microbe density of 130 organisms per cubic centimeter.^{8, 27} It will be shown that variations of that number could have a significant impact on the probability of contamination.

Table 3.1

BIO-BURDEN SUBMODEL PARAMETERS

Microbe Location	1 Presterilization Microbe Population		2 D-Value [‡]		3 Poststerilization Microbe Population [§]		4 Project Viking Estimates of Overall Population [*]
	Normal [*]	Hardy [†]	Normal	Hardy	Normal	Hardy	
External	6.8×10^4	170	1.95 hr	25 hr	2.8×10^{-11}	10.7	11
Covered	4.3×10^4	107.5	1.95 hr	25 hr	1.7×10^{-11}	6.8	16
Mated	460	1.1	3.85 hr	Infinity	7.42×10^{-6}	1.1	9
Encapsulated	94,000 [■]	235	16.26 hr	Infinity	2,603	235	20,000

Note: Sterilization regime is 113°C for 30 hours.²⁷

* Reference 19.

† 0.25 percent of normal microbe population.²⁹

‡ Reference 27.

§ Computed from Columns 1 and 2 using Eq. (3.1).

■ Spacecraft volume times average density of 130 spores/cc.²⁷

3.1.1.2 Recontamination

The recontamination issue can be modeled at several levels of detail. As a first approximation, we considered external surfaces only and represent recontamination uncertainty by the probability node in Figure 3.3. Since the lander is encased in the bioshield during and after the terminal heat sterilization process,²⁷ the most likely recontamination mode is a breach of the bioshield seal and subsequent entry into the bioshield by airborne organisms. For discussion purposes we have assigned a probability of 10^{-3} to this event, with an outcome of 100 additional organisms contaminating the external locations as the result of the recontamination event. The expected value of the probability node in Figure 3.3 is then 11.1 organisms in external locations. Given these numbers, recontamination does not constitute significant increase in the bio-burden.

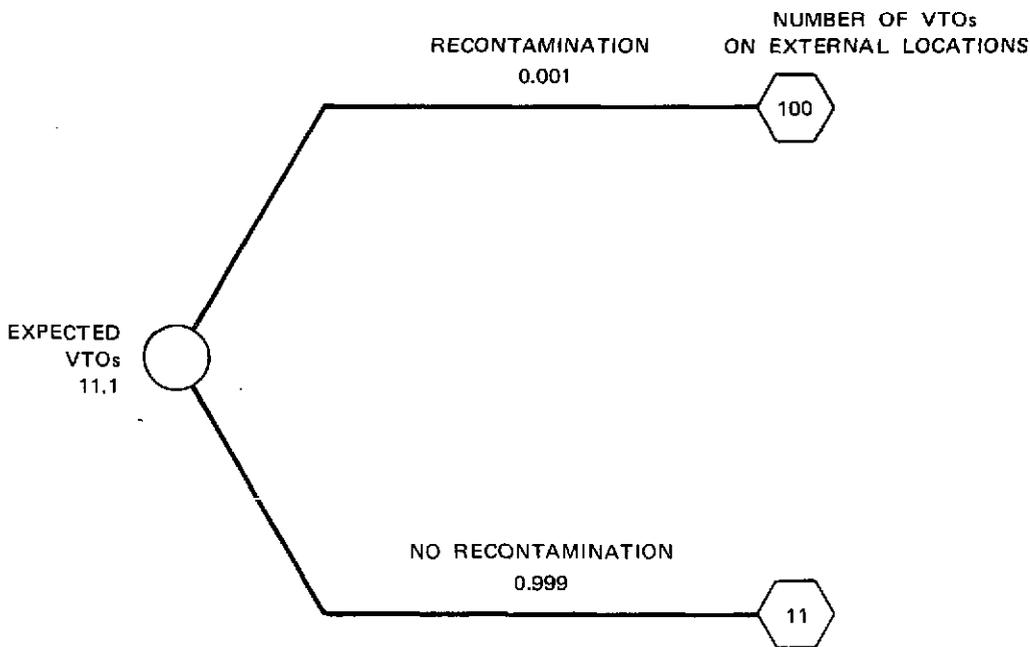


FIGURE 3.3 EFFECT OF RECONTAMINATION ON EXPECTED BIO-BURDEN

3.1.1.3 Contamination of the Bioexperiment

Contamination of the bioexperiment nutrient has also been cited^{27,30} as an issue of concern. If an organism were to penetrate the seal on the nutrient container or were located on the path of the nutrient during the conduct of bioexperiments, it is likely that extensive proliferation would occur. However, the probability of this event is currently constrained to be less than 10^{-6} .³¹ Given the location of the nutrient in sealed glass ampoules enclosed in a steel container and the limited interior surfaces that will be in contact with the nutrient during the bioexperiment, it is generally believed that the probability of nutrient contamination is much lower than 10^{-6} , although some estimates have been as high as 10^{-5} .³² Note that this event would also affect the validity of the data returned from the bioexperiment on Mars. However, contamination of the bioexperiment, if it occurs, will probably be caused by a single terrestrial microorganism and will therefore result in the formation of a pure culture.³¹ Martian organisms, if they exist, are likely to form a mixed culture. At least one of the bioexperiments on the spacecraft should be able to differentiate between pure and mixed cultures.³¹

Assuming that the mission will not be flown unless the 10^{-6} constraint is met, the total risk of planetary contamination as a result of bioexperiment contamination is negligible compared with other sources of planetary contamination. As will be shown in Subsection 3.4, 1 chance in 20 is assigned to the event that the species that would cause contamination of the nutrient will be adapted to survive and grow in the Martian environment. The risk of contamination of Mars by VTOs proliferating in the bioexperiment box is therefore bound to be less than 5×10^{-8} . This is a case where the assumptions implied in the Sagan-Coleman formula do not apply, but numerically the contribution

from bioexperiment contamination is negligible compared with the overall contamination probability.

3.1.1.4 Increase or Decrease of Microbe Population During Flight

Finally, we consider the in-flight increase or reduction in the number of organisms. From discussions with Mr. E. Bacon at Exotech,²⁷ we understand that NASA planning has assumed that neither proliferation nor reduction in load will occur during transit. Strict control on the organic material aboard the Viking lander and shielding of the lander by the aeroshell up to the descent phase make these assumptions reasonable.

3.1.2 Bio-Burden Submodel Summary

In summary, we have used Project Viking estimates of bio-burden profile for the output of the Bio-Burden Submodel. The numbers, by location, are given in Column 4 of Table 3.1. Given the current estimates, neither recontamination nor contamination of the bioexperiment is a critical issue, but we recommend that attention be given to these estimates as the project evolves and the terminal sterilization plan is reviewed.

3.2 The Release Submodel

The Release Submodel is used to represent the processes by which VTOs aboard the spacecraft are viably released into the Martian environment.

3.2.1 Release Submodel Parameters

The important input and output parameters for the Release Submodel are represented in Figure 3.4. The main input variable is the

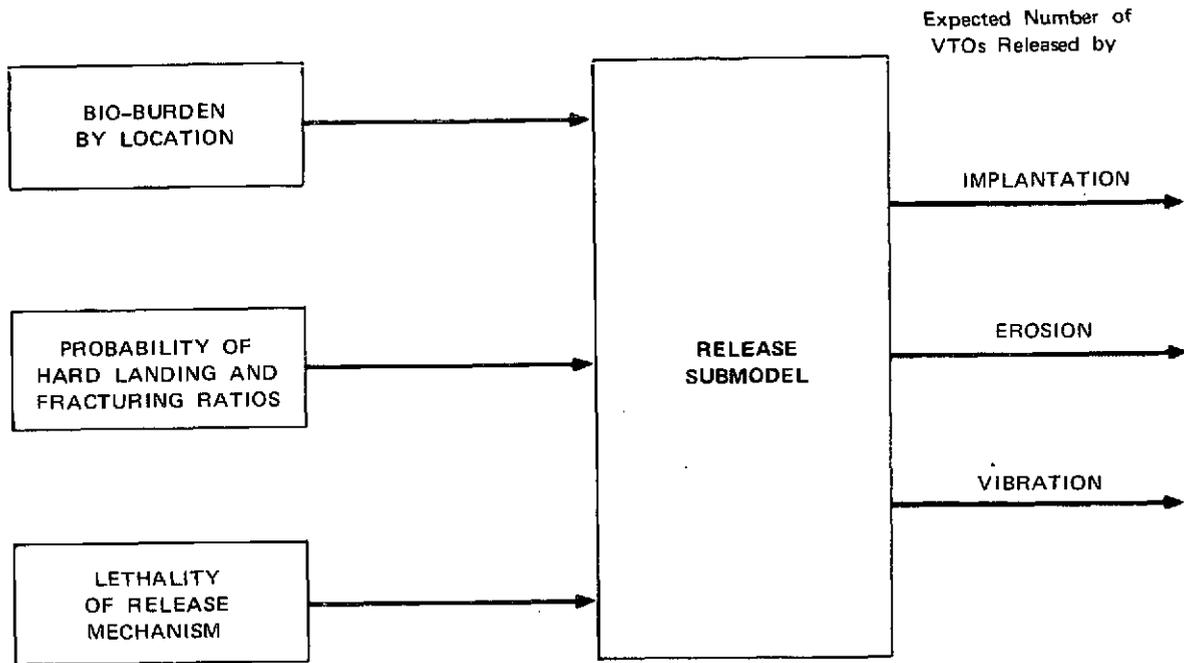


FIGURE 3.4 THE RELEASE SUBMODEL

bio-burden profile from the Bio-Burden Submodel. The Release Submodel treats uncertainty in landing mode, fracturing on hard impact, aeolian erosion as a release mechanism, and lethality of erosion and other release mechanisms.

The overall output from the model is the expected number of organisms released by erosion, implantation, or vibration. Implanted organisms are externally located microbes that make direct contact with the ground on impact. These spores have the distinct advantage of avoiding the lethal UV flux in transit to a possible liquid water micro-environment. Microbes on landing pads or on the parachute, or microbes buried in dust after a hard landing are examples of implanted organisms. We assume the lander geometry is such that it will not be the focus for formation of a dune that would eventually cover it and implant all organisms still on board. If the spacecraft were covered by a dune,

aeolian erosion would be prevented and only external organisms could be released, thus reducing the expected number of released VTOs.*

Erosion releases are defined to occur only during local or global dust storms. Sagan³⁸ suggests that the lander materials could be eroded to depths of centimeters during the 50-year quarantine period. Therefore, we shall assume all encapsulated organisms will be released by erosion.

The third output is the number of organisms released by vibration. This mechanism is defined to pertain only to external microbes, although these include organisms originally not in external locations but newly exposed to the environment by material fracturing after a hard landing. This category is loosely an "all other" class, with releases of the following kinds included: microbes falling off on impact; microbes blown off by winds; organisms shaken off by the lander's operational dynamics and vibration and by thermal effects.

* However, the VTOs released in this situation would be implanted. We might ask if the assumption of no dune formation could be a sensitive assumption. If a dune were to form over the spacecraft, we might expect all VTOs on external surfaces to be implanted. Suppose we assume a 1 percent chance of dune formation. Since presumably the external surfaces of the spacecraft are exposed to UV radiation for many days prior to the dune formation, we assume some mortality for nonshielded microbes. For example, we might assume that only 5 percent are still viable after several days exposure. Assuming an expected 11 VTOs located on the external surface of the spacecraft, the contribution of potential dune formation is then $11 \times 0.01 \times 0.05 = 0.006$, an increase of 13 percent in the expected number of organisms implanted. The effect on the overall probability of contamination would be an increase of 3 percent. Even if dune formation were certain, it would lead to an expected 0.6 VTOs implanted, which gives a contribution to the probability of contamination of about 1.5×10^{-5} . But in this situation the contribution from erosion release would be negligible. In summary, we do not regard dune formation as a sensitive issue.

3.2.2 Release Submodel Structure

Figure 3.5 is a tree representation of the various events pertaining to the release mechanism. The input bio-burden is introduced at the base of the tree (left) and is divided at any node among the successor nodes in proportion to the probability assigned to each branch. This is accomplished by simply multiplying the bioload at a node by the probability on one of its branches and assigning the product to the successor node at the end of that branch. When this is repeated for all nodes and branches in the tree, we are left with the total bio-burden input fractionated among 27 terminal nodes at the right of the tree.

As described above, the output from the Release Submodel is the expected number of VTOs released by each of three mechanisms: implantation, erosion, and vibration. To obtain these numbers, consider the terminal nodes at the right of the tree. Each of these nodes corresponds to either viable or nonviable organisms. Furthermore, each terminal node is linked to the base of the tree by a unique path and therefore, as we shall show below, corresponds to a specific release mechanism. Thus, it is a simple matter to identify terminal nodes corresponding to viable organisms, to sort them according to the release mechanisms, and to sum their contributions to obtain the expected number of VTOs released by each of the three mechanisms.

To acquaint the reader with the primary state variables in the Release Submodel tree, we will describe the four node levels shown in Figure 3.5. The names of the node levels are shown at the top of that drawing.

The first set of nodes represents the location of the microbes. This information is the output bio-burden profile from the Bio-Burden Submodel: the expected number of VTOs in external, covered, mated, and encapsulated locations. The second set of nodes in the model refers to

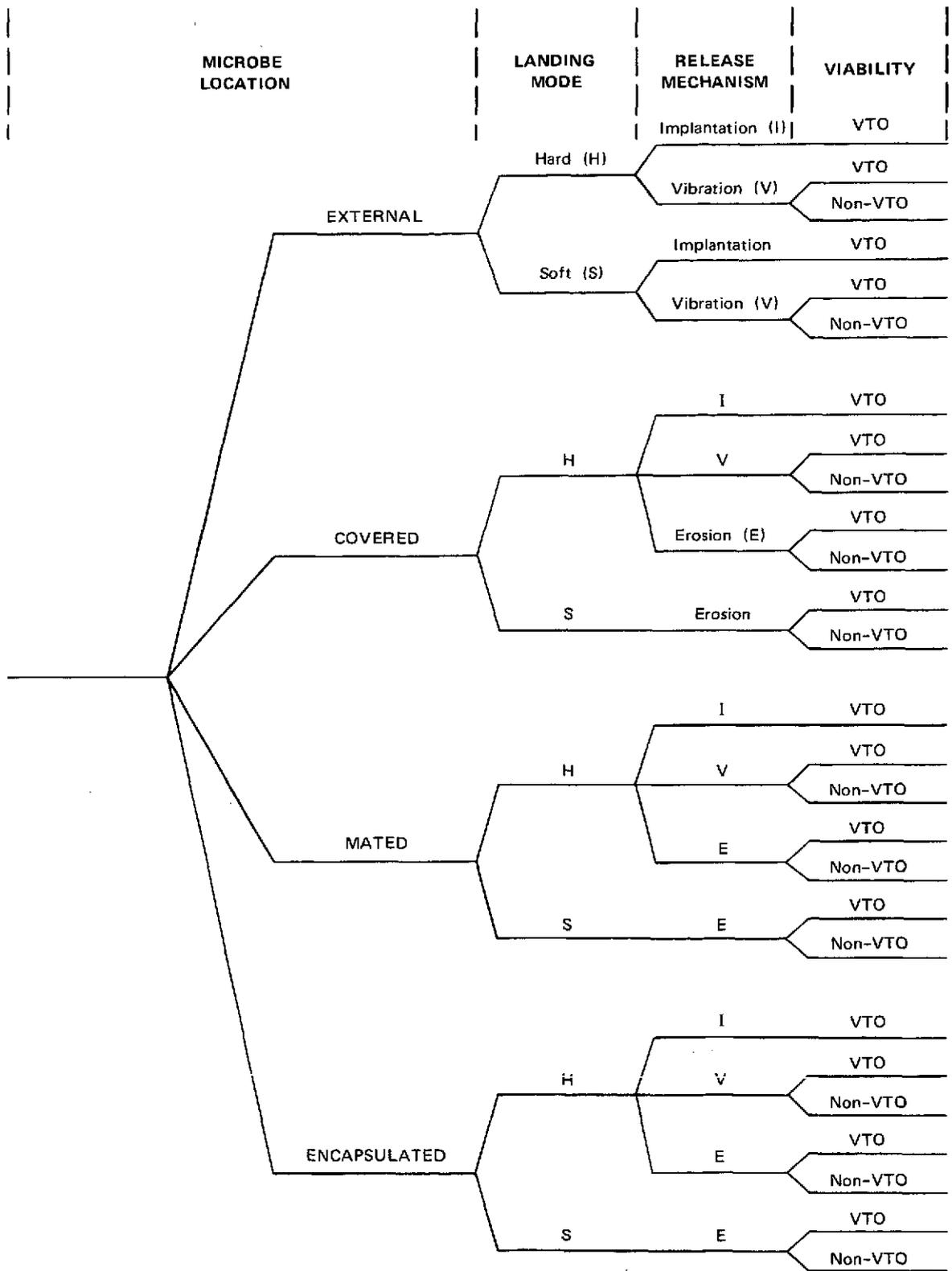


FIGURE 3.5 TREE STRUCTURE FOR VTO RELEASE

the landing mode of the capsule. Two landing modes are represented: hard and soft (nominal). The third set of nodes characterizes the release mechanisms described above. The fourth set of nodes concerns the viability of the organism after release. A major consideration here is whether the release process (aeolian erosion, for instance) is lethal to the organisms. The expected numbers of VTOs released by each of the three release mechanisms are the state variables passed to the Transport Submodel.

We shall now look more closely at each of the nodes. The first four branches in the tree characterize the location of the bio-burden. Associated with each of these branches is the expected number of organisms in each location.

The probability of a hard landing is independent of the location of microorganisms on the lander. In this submodel we have taken as representative of a hard landing an impact having mean velocity of 1,000 feet per second, as might result from a malfunction of the vernier engine. The probability assigned to a hard landing is 0.002.³⁴ At this impact velocity we can expect rupture and deformation, but we would not expect extensive fragmentation or powdering of the lander materials.³⁵ Assumptions about this impact velocity strongly influence the modeling of subsequent release mechanisms. One additional assumption is that all microorganisms that are still viable immediately preceding the impact will not be killed by a hard landing. This is supported by work performed by the Boeing Company, in which the lethality of impacts below 1,500 feet per second was nil.³⁶

As shown at the top of Figure 3.5, after "Landing Mode" we consider the "Release Mechanism." For the covered, mated, and encapsulated branches, the tree structure and release mechanisms are the same, although the branches have different fractions. To describe the structure we pick a trajectory through the tree beginning with a mated location microbe.

Again, the structure is the same for covered or encapsulated organisms. After a hard landing a fraction of those organisms that were formerly in a mated location can be considered to be on an exposed surface, owing to fracturing of the lander. We will refer to this fraction of microorganisms as that fraction newly exposed (f_{ne}) by the hard landing. Of these newly exposed organisms, some, just as on the external branch, are implanted during impact and others are released by vibration. The remaining "unexposed" fraction of the organisms ($1 - f_{ne}$) is subjected to the aeolian erosion process like the mated organisms after a soft landing. As can be seen in Figure 3.5, there is a certain lethality associated with both the vibration release mode and the erosion process.

The odds of a surface microbe being released by implantation rather than by vibration are influenced by the landing mode. In the nominal soft landing mode, only the viable microbes on the bottom of the landing pads will be implanted. However, on a hard impact of 1,000 feet/sec and subsequent break-up of the craft, most pieces of the lander will be on the surface or partially buried. Thus a much greater fraction of the newly exposed organisms will be implanted. As stated before, we are not formally including in our analysis the formation of a dune over the spacecraft.

To compute the number of organisms released that were initially on a mated surface, conditional on a hard landing, we need to know four separate parameters:

- (1) the fraction of microorganisms newly exposed f_{ne} (mated).
- (2) the portion of newly exposed organisms that are implanted.
- (3) the fraction of organisms that survive vibration release.
- (4) the lethality of the aeolian erosion mechanism.

As stated before, the structure described for the mated surfaces is identical for covered and encapsulated microorganisms. The table in Figure 3.6 contains values for these parameters for each of the four locations. The table also shows the tree structure for the covered, mated, and encapsulated branches. The computation of branch fraction from the table is demonstrated symbolically on the tree below the table.

Figure 3.7 shows the assignment of branch probabilities to the Release Submodel. A detailed description of each assignment is given in Appendix B.

3.2.3 Release Submodel Summary

Depending on the release mechanism, the organisms may be subjected to a variety of transport processes before they reach a hospitable microenvironment. The contributions of each release mechanism will therefore have a specific impact on the probability of contamination. The Transport Submodel presented in Section 3.4 will show that organisms released by implantation have about 100 times as much chance of growth as organisms released by erosion and 5 times as much chance as organisms released by vibration.

With this information in mind, the number of VTOs released by each of the three mechanisms should be reviewed. Calculations from Figure 3.7 show that:

- (1) The implantation mechanism operates essentially on VTOs on external surfaces and encapsulated in solid materials. The following breakdown shows three dominant possibilities contributing to a total of 0.045 VTOs released by implantation.

MICROBE LOCATION	a f_{ne} (1) - fraction newly exposed	b portion of f_{ne} Implanted	c fraction surviving Vibration	d fraction surviving Erosion
EXTERNAL OR NEWLY EXPOSED	1.0	0.5 (5rel)	10^{-2} (6rel)	No erosion
COVERED	0.1 (2rel)	—	—	0.8 (7rel)
MATED	0.1 (2rel)	—	—	10^{-2} (8rel)
ENCAPSULATED	10^{-3} (3rel)	—	—	10^{-4} (9rel)

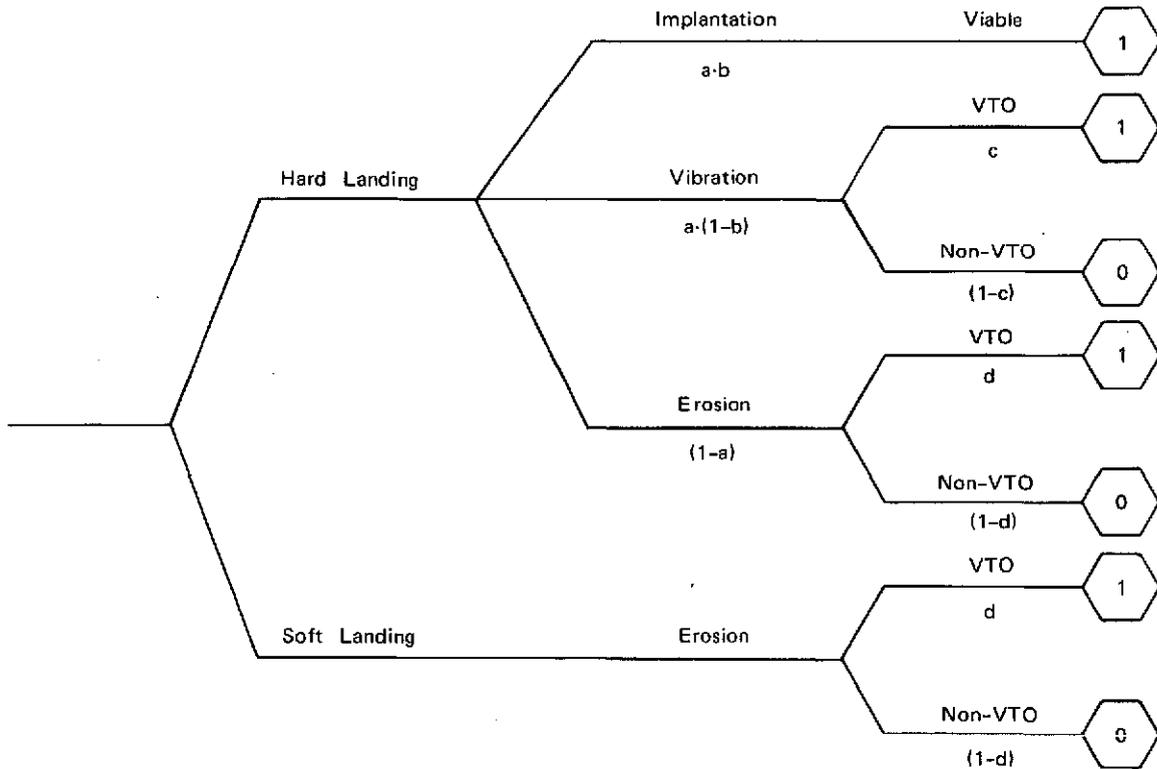


FIGURE 3.6 RELEASE SUBMODEL PARAMETERS

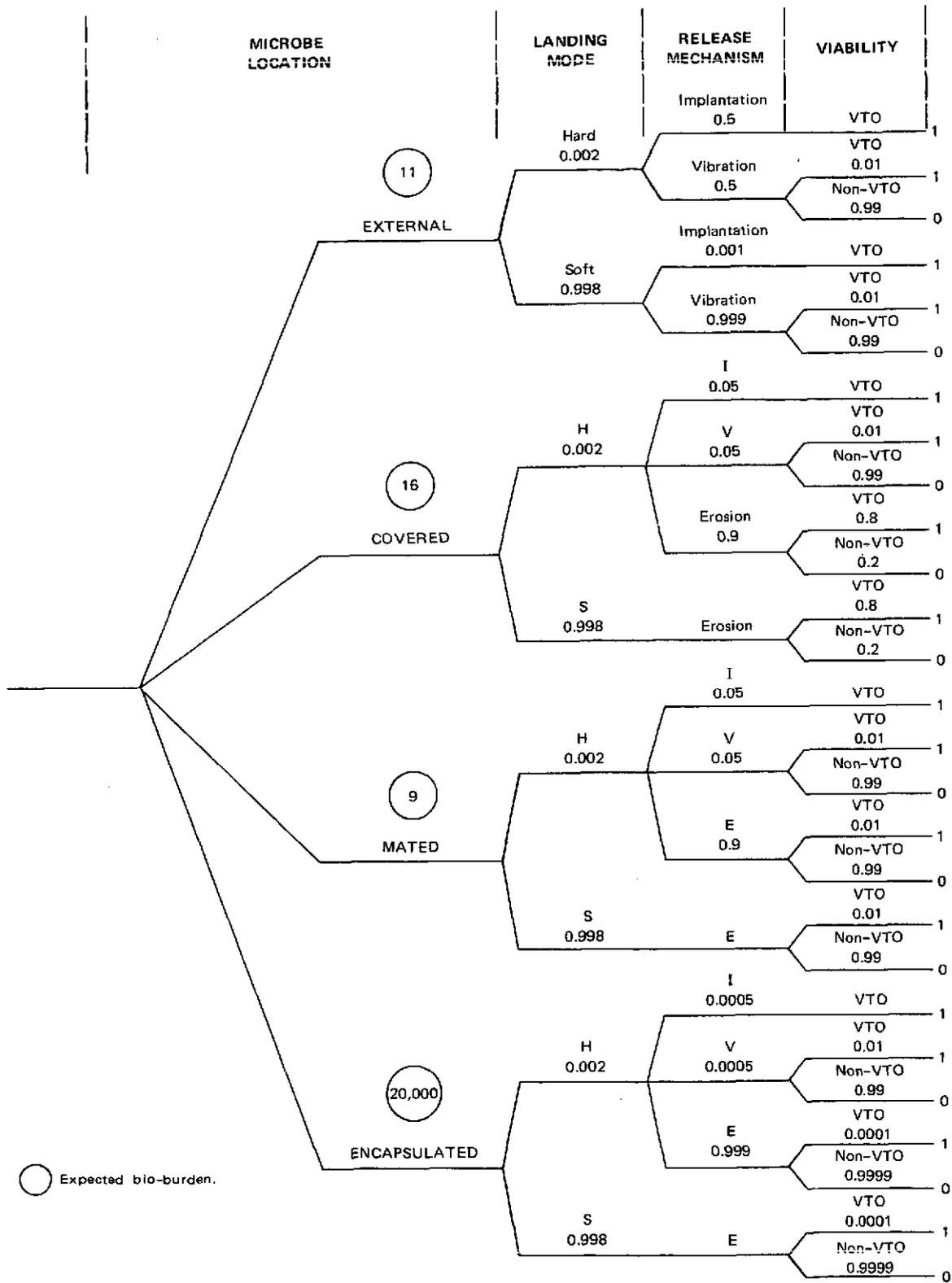


FIGURE 3.7 TREE STRUCTURE FOR VTO RELEASE: PARAMETERS

<u>Number of VTOs per Location Type</u>	X	<u>Probability of Landing Mode</u>	X	<u>Other Release Parameters (see Table 2.1)</u>	=	<u>Expected Number of VTOs Released by Implantation</u>
External 11	X	Hard landing 0.002	X	(5rel) 0.5	=	0.011
External 11	X	Soft landing 0.998	X	(4rel) 0.001	=	0.011
Encapsulated 20,000	X	Hard landing 0.002	X	(3rel)(5rel) 0.001 × 0.5	=	0.020
Others						<u>0.003</u>
Total						0.045

- (2) The expected number of VTOs released by erosion is 14.89 and consists essentially of VTOs on covered surfaces and encapsulated.

<u>Erosion Type and Number of VTOs Released</u>	X	<u>Probability of Type of Landing</u>	X	<u>Other Release Parameters (see Table 2.1)</u>	=	<u>Expected Number of VTOs Released by Erosion</u>
Covered 16	X	Soft landing 0.998	X	(7rel) 0.8	=	12.80
Encapsulated 20,000	X	Soft landing 0.998	X	(9rel) 0.0001	=	2.00
Other						<u>0.09</u>
Total						14.89

- (3) The vibration release mechanism contributes a total expected number of 0.11 VTOs. Practically all were located on external surfaces and are released by vibration following a soft landing.

<u>Location Type and Number of VTOs Released</u>	<u>Probability of Type of Landing</u>	<u>Other Release Parameters (see Table 2.1)</u>	<u>Expected Number of VTOs Released by Vibration</u>
External 11	Soft landing 0.998	(6rel) 0.01	0.11

Table 3.2 presents the output of the Release Submodel in the form of a Release Submodel matrix. Each element of the matrix represents the probability that a microbe in a given location will be released by a specific release mechanism.

The most important elements are marked by asterisks. It is also clear from this table that organisms on mated surfaces play a negligible role.

Table 3.2

RELEASE SUBMODEL MATRIX: PROBABILITY THAT A SINGLE VTO IN EACH LOCATION WILL BE RELEASED BY EACH MECHANISM

Expected Number of VTOs Released by Each Mechanism	Expected Number of VTOs in Each Location			
	External 11	Covered 16	Mated 9	Encapsulated 20,000
Implantation 0.045	$2 \times 10^3^*$	10^{-4}	10^{-4}	10^{-6}^*
Erosion 14.89	0	0.8^*	0.01	10^{-4}^*
Vibrating 0.01	10^{-2}^*	10^{-7}	10^{-7}	10^{-9}

* Most important elements.

3.3 The Transport Submodel

If a viable microbe has been released, it must reach a hospitable environment in order to proliferate and cause contamination. Several questions arise: If there is no water where the microbe first contacts the planet, how does it move to other water sources? Is the available water "usable"* by the microbe? What is the microbe's resistance to the hostile UV radiation? If resistance is low, does the microbe survive because of shielding from UV radiation?

These questions are addressed in the Transport Submodel, as shown in Figure 3.8. The primary transport mechanism is Martian winds. The microbe, depending on its size and attachment to other particles, is either carried aloft like dust or caught in a saltation† process at the surface. The model will produce as an output the expected number of organisms reaching a source of usable water.

3.3.1 Markovian Models

We have chosen a Markov model to represent the dynamics and uncertainty of transport on the Martian surface. Crucial to the use of the Markov representation is the concept of a state, which we shall explain briefly by paraphrasing the text of R. A. Howard.³⁷

* Terrestrial organisms do not necessarily require liquid water. Some organisms are known to live on water vapor (with sufficiently high partial pressure), or on ice at temperatures greater than -10°C , or on water contained in nutrients.

† Saltation refers to the movement of sand particles near the surface in a storm. Bouncing or leapfrog trajectories are followed by the relatively heavy sand particles.

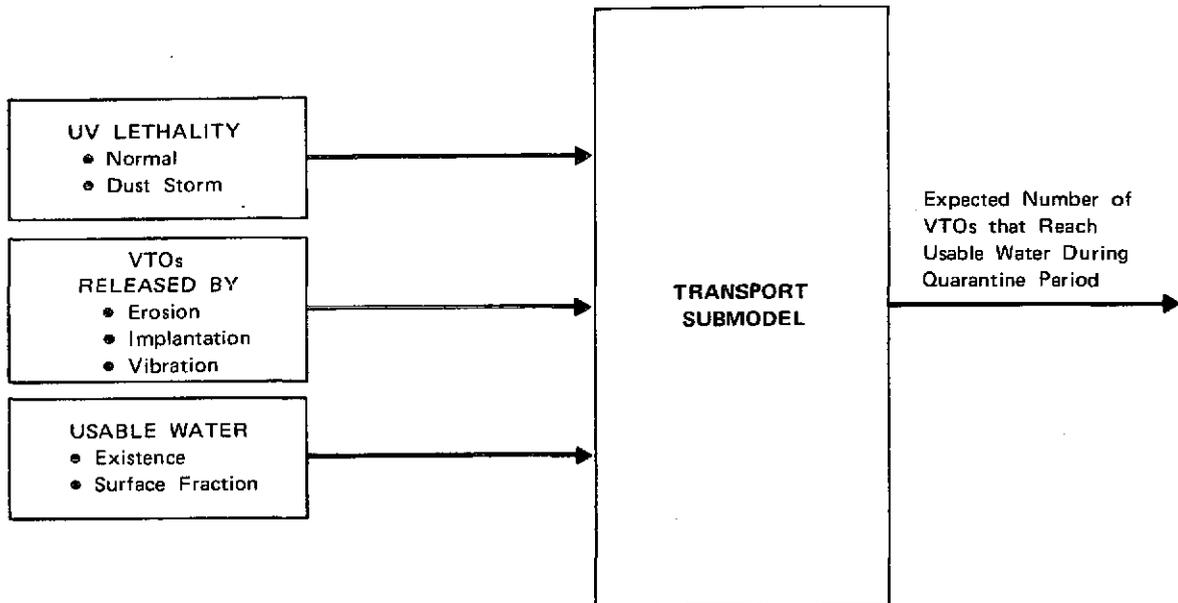


FIGURE 3.8 THE TRANSPORT SUBMODEL

The "situation" of a microbe on the Martian surface can be specified by giving the value of several variables that describe the microbe relative to the transport system. These variables are called state variables, and they answer questions like: Is the microbe alive or dead? Has it been released from the lander? Is it aloft and being blown by the winds or is it lodged in sand? Is it shielded from UV radiation? Is it in a water microenvironment?

As surface dust storms come and go, the state description of the microbe is likely to change. Since Martian dust storms provide the most probable means of transport from the lander to usable water, it is very important that our model of transport represent the dynamic effects of the local or global dust storms.

3.3.1.1 A Three-State Model

As a very simple model, consider the state descriptions shown in Figure 3.9. There is only one state variable: the physical location of the microbe. The values that variable can have are: (1) on the lander, (2) in transit, or (3) lodged in dust. Thus, this simple model includes a provision for the dynamics of dust storms. Also, the three states are mutually exclusive--a property that will be discussed later.

Assume the microbe is released from the lander by the first local dust storm. According to the model in Figure 3.9, it then makes the transition from the "Microbe on Lander" state to the "Microbe in Transit" state. This transition is indicated by the one-way arrow in the drawing. Associated with this transition is the local dust storm event. As the storm dies, we can imagine that the microbe falls to the ground and becomes lodged in an accumulation of dust. Hence,

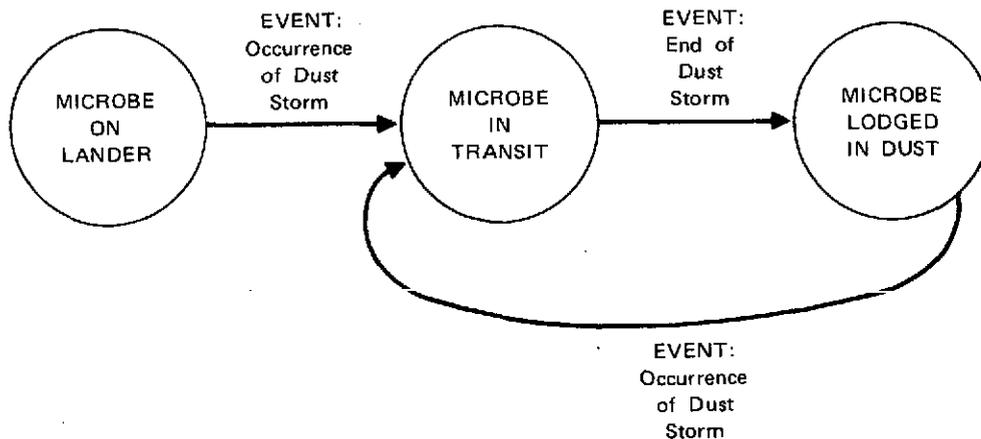


FIGURE 3.9 THREE-STATE REPRESENTATION OF MICROBIAL TRANSPORT

the transition to the third state, with the end of the storm as the associated event. Notice that the transitions are caused by the occurrence of events and are not related to the passage of set periods of time.

With the onslaught of the next dust storm, the microbe makes the loop transition: it reenters the "Microbe in Transit" state. Thus the process continues for as long as there are dust storms to provide a transport mechanism.

3.3.1.2 A Five-State Model

The three-state model can be enhanced by including a provision for the death or permanent immobilization of the microbe. This will be especially useful in the context of planetary quarantine because once a microbe enters the "Nonviable" state we no longer are concerned with it. Figure 3.10 shows the nonviable state and includes a state representing the microbe in a usable water microenvironment. In the latter state the organism is assumed to be no longer "available" for transport. In fact, the microorganisms that reach usable water will be the output state variable for the entire Transport Submodel. Note that once a microbe has entered either of these new states, it can never leave. These are therefore called "trapping states" and are indicated in the figure by circles drawn with bold lines. These two states are mutually exclusive since all dead organisms are in the nonviable state.

The transition process has now been complicated by the addition of several arrows emanating from the "Lodged in Dust" state. These arrows correspond to the physical situation where some of the lodged organisms are actually in a usable water microenvironment. Others are lodged but dead, probably as a result of soil abrasion in the storm, or UV radiation while left on the ground after the storm, or

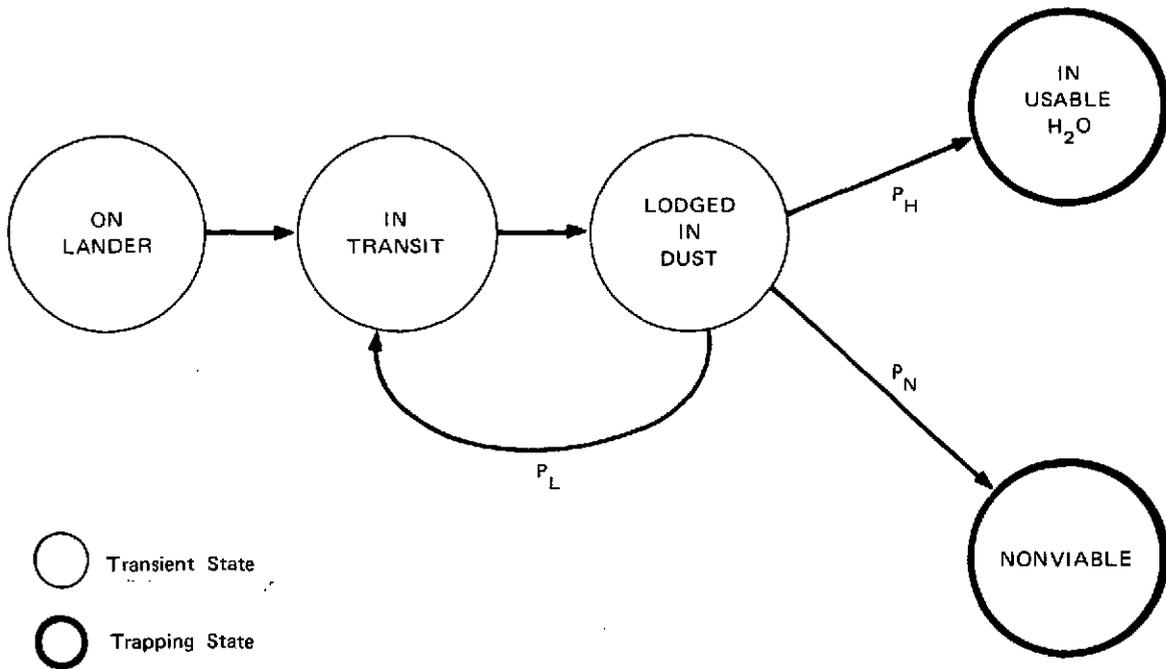


FIGURE 3.10 FIVE-STATE REPRESENTATION OF MICROBIAL TRANSPORT

other causes such as the freeze-thaw cycle. The remaining microbes are not permanently lodged and may be put in transit by another dust storm.

To specify the fraction of lodged organisms that are in a microenvironment with water and the fraction that are nonviable, we assign probabilities P_H and P_N . Thus, an organism that is lodged at the end of a storm has a probability (P_H) that it will be in water and a probability (P_N) that it will be lodged but nonviable. The probability that the microbe will not be available for transport by the next dust storm is ($P_H + P_N$). In other words, the probability that the microbe will be put into the "In Transit" state by the next dust storm is:

$$P_L = 1.0 - (P_H + P_N) .$$

This result is correct only if the states are mutually exclusive.

One more point relative to the five-state model in Figure 3.10 deserves to be mentioned. The transitions from "Lodged in Dust" to "In Usable H₂O" or "Nonviable" are not necessarily caused by the same events that cause transition from "In Transit" to "Lodged in Dust." In fact, the transitions to either of the trapping states could occur any time between the end of one dust storm and the beginning of the next. These transitions do not affect the event-based dynamics of the three-state model as long as we carefully define the time period in which each transition can occur.

Figure 3.11 defines the time periods by introducing one final new term: the dust storm cycle. Since the dynamic transport process is based on dust storm events, this cycle will take on special significance. Passage of one cycle indicates not only that a dust storm has started and ended, but also that the opportunity for making any of the transitions in the model has occurred only once. This will be very useful when determining the fraction of organisms that have reached water after the first dust storm following their release from the spacecraft. To be precise, one cycle includes the period from the beginning of one storm to the beginning of the next.

3.3.2 The Transport Submodel: A Six-State Markov Model

Despite the addition of a time frame, the five-state model is still lacking in that it does not allow the possibility of an organism becoming Nonviable while "In Transit." Also, it does not distinguish between the inputs from the three release mechanisms discussed earlier.

This situation can be remedied as shown in Figure 3.12. The "In Transit" state is replaced by two new states: "Dustborne" and "Survived Transit." A microbe in the "Dustborne" state will not necessarily reach the "Survived Transit" state but may become "Nonviable."

TRANSITION
BETWEEN STATES

TIME TRANSITION OCCURS

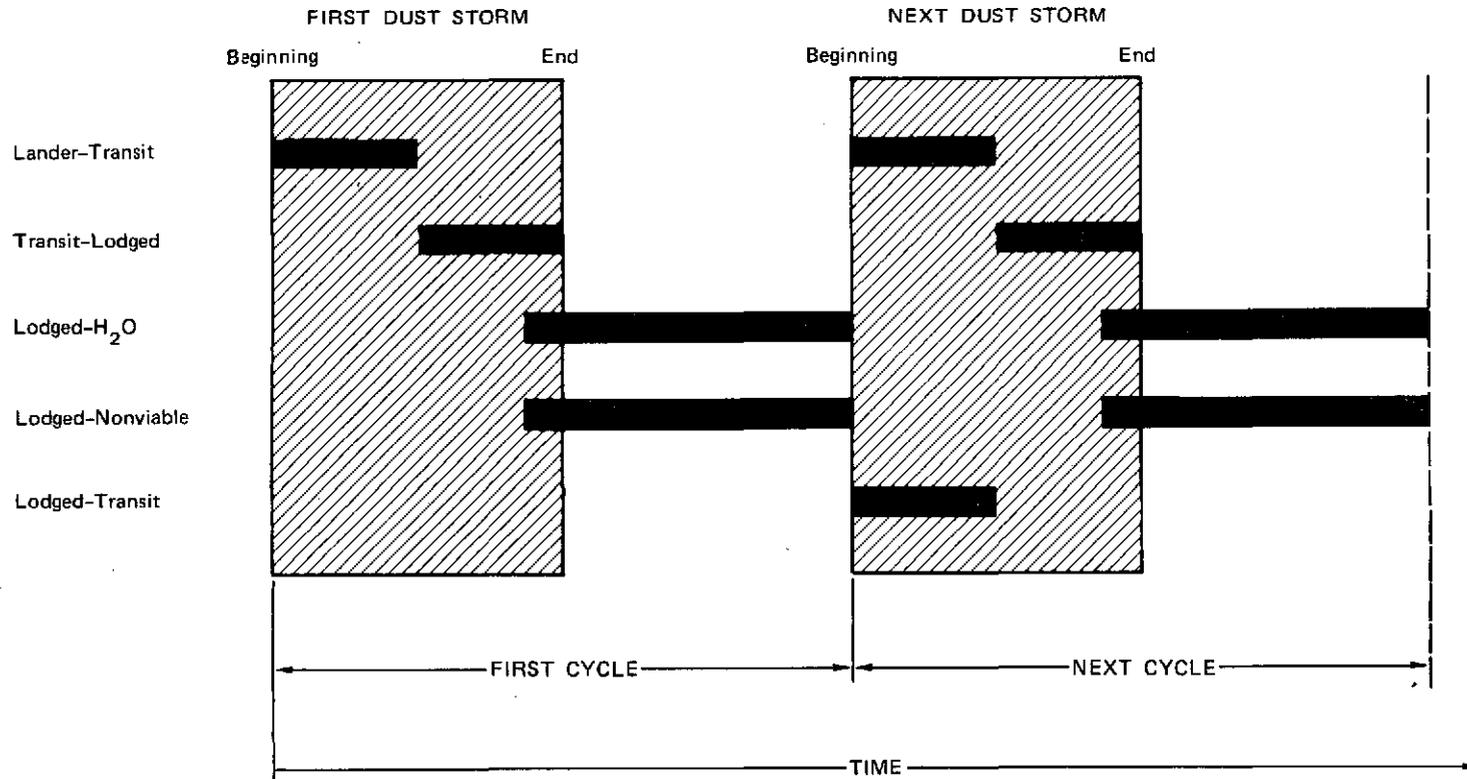
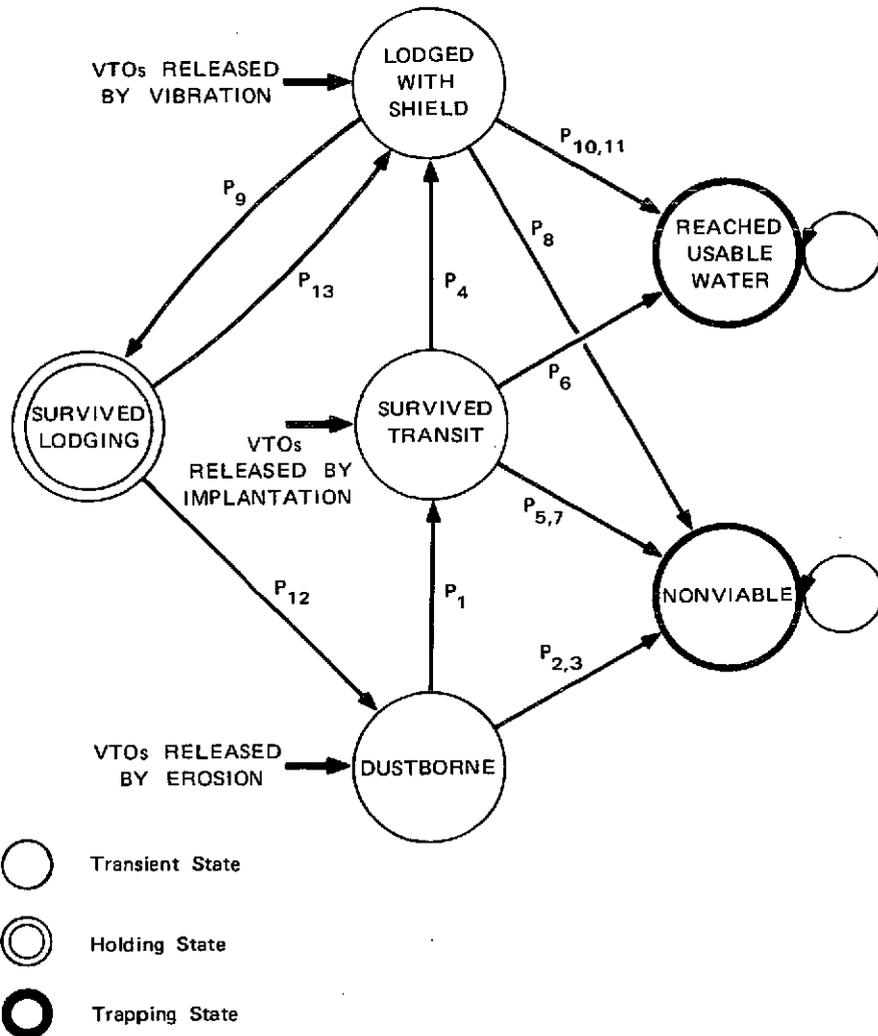


FIGURE 3.11 FIVE-STATE REPRESENTATION OF DUST STORM CYCLE



P_i 's refer to transition probabilities between states. See Section 3.3.3.

FIGURE 3.12 TRANSPORT MARKOV MODEL

Likewise, VTOs having "Survived Transit" can become "Nonviable" when the dust storm subsides because of a lack of shielding from UV radiation. The old state "Lodged in Dust" now refers only to the VTOs that survive transit and find sufficient protection from UV radiation when they are dropped by the dust storm, and is therefore renamed "Lodged with Shield."

The old "On Lander" state is replaced by three arrows () pointing to the three states, "Dustborne," "Survived Transit," and "Lodged with Shield," where VTOs can enter the transport process, as will be explained shortly.

Finally, the Transport Submodel must reflect the dependence of transport mechanisms on the occurrence of dust storms. At the end of a dust storm, VTOs may be in one of the two trapping states, "Reached Usable Water" and "Nonviable," or "Lodged with Shield," waiting for the onslaught of the next storm. However, we want to recognize the fact that water might be deposited on a VTO lodged with shield or that the organism might reach water by an alternate transport mechanism before the beginning of the next storm. A VTO might also be killed while lodged with shield by environmental conditions other than the UV radiations (for example, by the diurnal freeze-thaw cycle). For these reasons, a VTO can make a transition out of the "Lodged with Shield" state before the occurrence of a new dust storm. To indicate when a VTO might be picked up by a new dust storm, we therefore define a sixth state, "Survived Lodging," corresponding to VTOs that between two storms remain lodged in a viable state but without access to usable water. This is in effect a "holding" state, which is represented in Figure 3.10 by a double circle.

Similar to Figure 3.11, Figure 3.13 shows the dust storm cycle and the time periods in which transitions may occur. Note

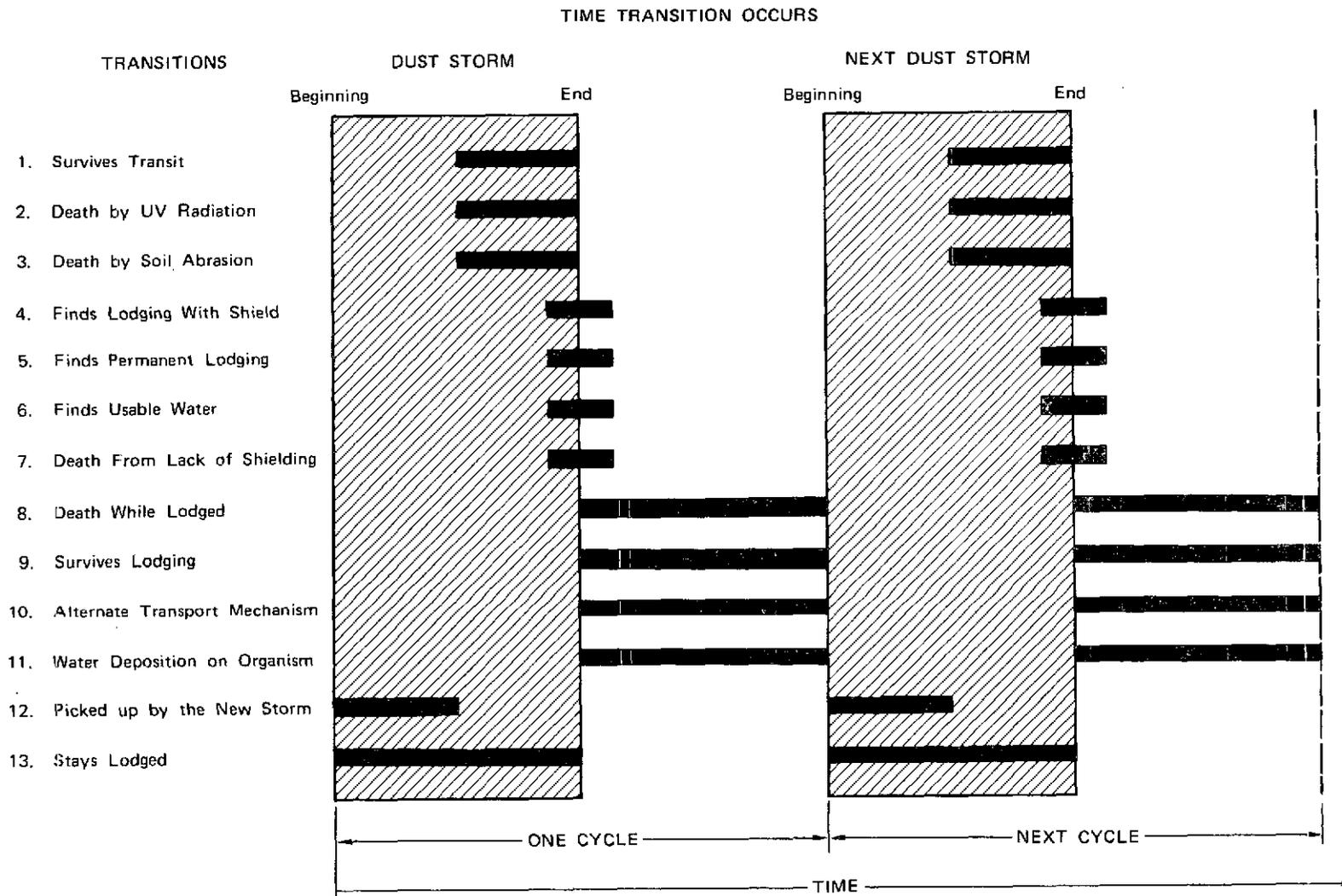


FIGURE 3.13 TRANSPORT MARKOV MODEL—DUST STORM CYCLE

in Figure 3.13 that the two transitions out of "Survived Lodging" (Transitions 12 and 13) are the only two that occur at the beginning of the cycle.

A last point must be discussed concerning the use of a Markov model. Theoretically, a Markov model imposes a constraint on all transition probabilities: "Only the last state occupied by the process is relevant in determining its future behavior."³⁷ This means that, for instance, transition probability P_8 in Figure 3.12 cannot be dependent on whether the state occupied before "Lodged with Shield" was "Survived Lodging" or "Survived Transit." Although we feel this assumption is justifiable, its adoption will be shown to be an almost moot point because most of the released organisms either will be killed or will reach a usable water environment during the first cycle--a major conclusion to be amplified later.

3.3.3 Transport Submodel Parameters

A brief summary of characteristics of the Transport Submodel is given below. It includes definitions of the six states in the submodel, descriptions of the transitions between states, and identification of the states in which released microbes enter the Transport Submodel. More complete descriptions and quantitative assessments of the parameters are given in Appendix C.

3.3.3.1 Definitions of the Six States

The six transport states of microorganisms are as follows:

Dustborne--All viable organisms involved in the aeolian erosion process. They might be aloft or saltating near the surface.

Survived transit--All VTOs surviving transportation at the end of a dust storm.

Lodged with shield--Microbes that are lodged with sufficient shielding to survive UV radiations between dust storms.

Survived lodging--All VTOs in dry locations but not permanently lodged or dead at the beginning of a dust storm cycle (a holding state).

Nonviable--All organisms that are dead, permanently lodged in a dry environment, or otherwise incapable of reproduction (a trapping state).

Reached usable water--All VTOs that have reached usable water or are lodged in a spot where water will develop for sufficient periods of time to allow reproduction (a trapping state).

3.3.3.2 Transition Descriptions and Probabilities

Figure 3.14 shows the probability assignments for each transition, which are based on discussions with experts. (Appendix C provides a detailed description of each of these transitions and probability assignments.) The brief summary supplied here should be sufficient for the reader to interpret Figure 3.14. The transitions are described in the order that they are numbered in Figure 3.13; the probability assignments are shown in parentheses.

Survive transit (10^{-2})--This transition is taken if the microbe survives the soil abrasion and attenuated UV radiation that is characteristic of dust storms^{32,38} (1tra).

Death by UV radiation (0.99)
Death by soil abrasion (~0) } The complement of Transition 1.

Find lodging with shield (0.5)--The microbe must find UV shielding to survive at the end of a dust storm (3tra).

Permanently lodged (~0)--If a VTO becomes unavailable to the transport process and is not in water, we consider it nonviable.

Find water (5×10^{-3})--We consider two primary water existence mechanisms: one proposed by C. B. Farmer³⁹ and one by A. P. Ingersoll.⁴⁰ [See Table C.4 in Appendix C (2tra)].

Death, given transport survival (0.495)--The primary cause here is inability of a VTO to find lodging with UV shield after the storm.

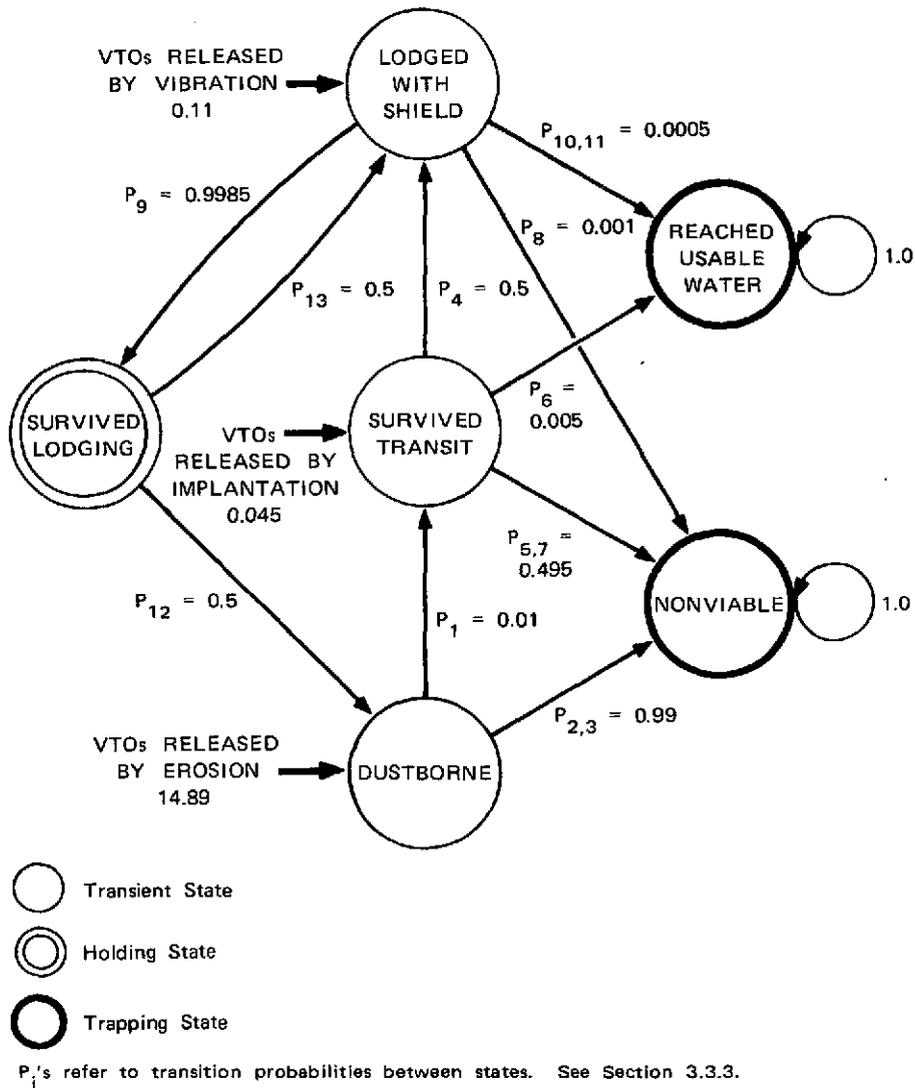


FIGURE 3.14 TRANSPORT MARKOV MODEL: PROBABILITY ASSIGNMENTS

Death while lodged (10^{-3})--Nonviability caused by temperature cycling or other environmental hazards, with the exception of UV radiations (6tra).

Survive lodging (0.9985)--The complement of Transitions 8, 10 and 11.

Alternate transport mechanism (5×10^{-6})--A means to reach water by other than storm transport during one dust storm cycle: vibration, earthquakes, and the like.

Water deposition on organism (5×10^{-4})--A rare event, covering all water encounters during one dust storm cycle not treated by Transitions 6 and 10 (4tra). Note that because of the 50/50 chance of a microbe staying lodged during a dust storm (Transition 13), Transitions 10 and 11 correspond to probabilities of 10^{-5} and 10^{-3} , respectively, during the 50-year quarantine period.

Swept aloft by a new storm (0.5)--Microbes "swept" into transit by a new storm cycle (5tra).

Stay lodged (0.5)--Microbes not picked up by the next new storm but potentially available for transport at a later period.

3.3.3.3 Microbe Starting States

Recall that the release model provides the expected number of VTOs released by three separate mechanisms: erosion, implantation, and vibration. This information is necessary to determine the starting state of the VTO population entering the transport process. Clearly, microbes released by aeolian erosion start in the "Dustborne" state, as shown in Figure 3.14.

Consider now the implanted organisms that were placed in contact with the ground during landing. We can assume they are shielded from UV flux and are able to find water with the same probability as an organism just deposited (shielded) at a random spot by a storm. We therefore make the assumption that implanted microbes begin in the "Survive Transit" state.

Finally, we must assign a starting state to organisms released from external locations by vibration. This release is expected to occur during nonstorm periods, a time when the UV flux tends to reach its maximum. Since these organisms are released in a viable condition, we assume they are in some way shielded from the lethal UV flux and we start them in the "Lodged with Shield" state.

3.3.4 Transport Submodel Results and Sensitivity Analysis

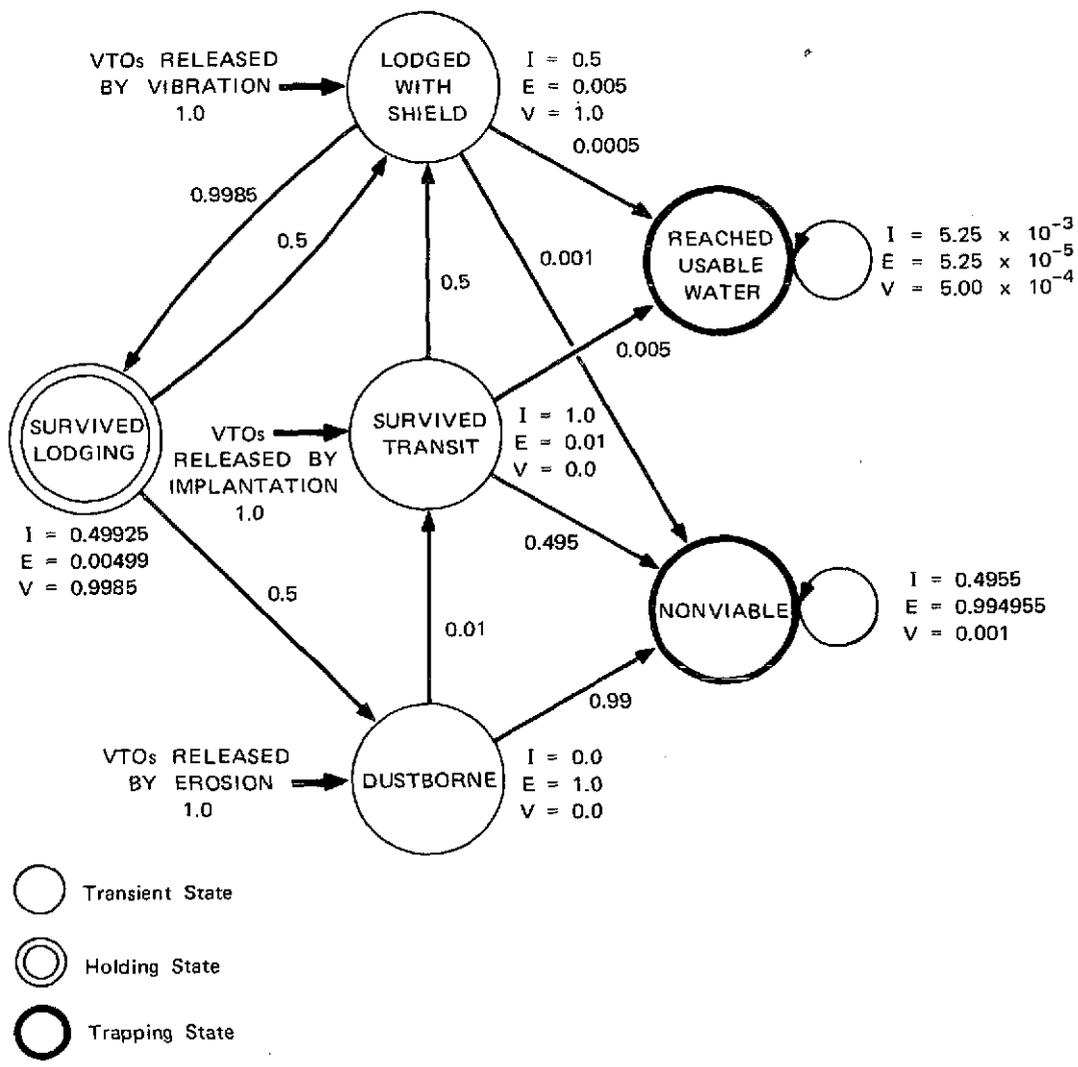
A direct inspection of the Transport Submodel described in Figure 3.15 reveals the major properties of the transport process and the critical variables. These results will then be confirmed and made more nearly precise by applying standard Markov process analysis techniques.

3.3.4.1 Direct Inspection of the Transport Submodel

Consider transport of a VTO during the first dust storm cycle following its release. Figure 3.15 indicates the probability that a VTO will occupy each of the states en route to water after one cycle. The tables next to each state identify the origin of the VTO: I = implantation, E = erosion, and V = vibration.

For example, a VTO released by erosion will enter the "Dustborne" state and will survive transit with probability 0.01. After the storm dies out, that VTO may be deposited in a microenvironment with usable water with probability 0.005 or may reach water by some other means after being lodged with shield with probability $0.5 \times 0.0005 = 2.5 \times 10^{-4}$. The total probability that an organism released by erosion will reach usable water in a viable state at the end of the first dust storm cycle is therefore:

$$0.01 \times (0.005 + 2.5 \times 10^{-4}) = 5.25 \times 10^{-5} .$$



P_{ij} 's refer to transition probabilities between states. See Section 3.3.3.

FIGURE 3.15 TRANSPORT SUBMODEL SHOWING THE PROBABILITY THAT A VTO WILL OCCUPY EACH STATE OF THE TRANSPORT SUBMODEL DURING THE COURSE OF ONE DUST STORM CYCLE

A similar reasoning shows that the probabilities that VTOs released by implantation or vibration will reach microenvironments with usable water during the first cycle following their release are 5.25×10^{-3} and 5×10^{-4} , respectively.

At the end of the first cycle following their release, VTOs that have not reached one of the two trapping states, "Reached Usable Water" or "Nonviable," are held in the "Survived Lodging" state until the beginning of the next dust storm.

During the new cycle those VTOs have equal chances of staying lodged and of being blown off by the new storm. In the latter case they will be exposed to dangerous UV radiations and their population will be reduced by two orders of magnitude. Therefore, their chances of reaching a microenvironment with usable water become negligible. On the other hand, if they stay lodged, they will again face the 5×10^{-4} probability of contacting usable water during the new dust storm cycle. It can be seen that the effect of the loop between the "Lodged with Shield" and "Survived Lodging" states is to return half of the "Survived" population to the "Lodged" state at the end of each cycle. This is equivalent to doubling the transition probabilities out of the "Lodged with Shield" state toward the two trapping states. Figure 3.16 depicts this simplified version of the Transport Submodel.

Using this approximation, the probability that a VTO eventually reaches a microenvironment with usable water is as indicated below:

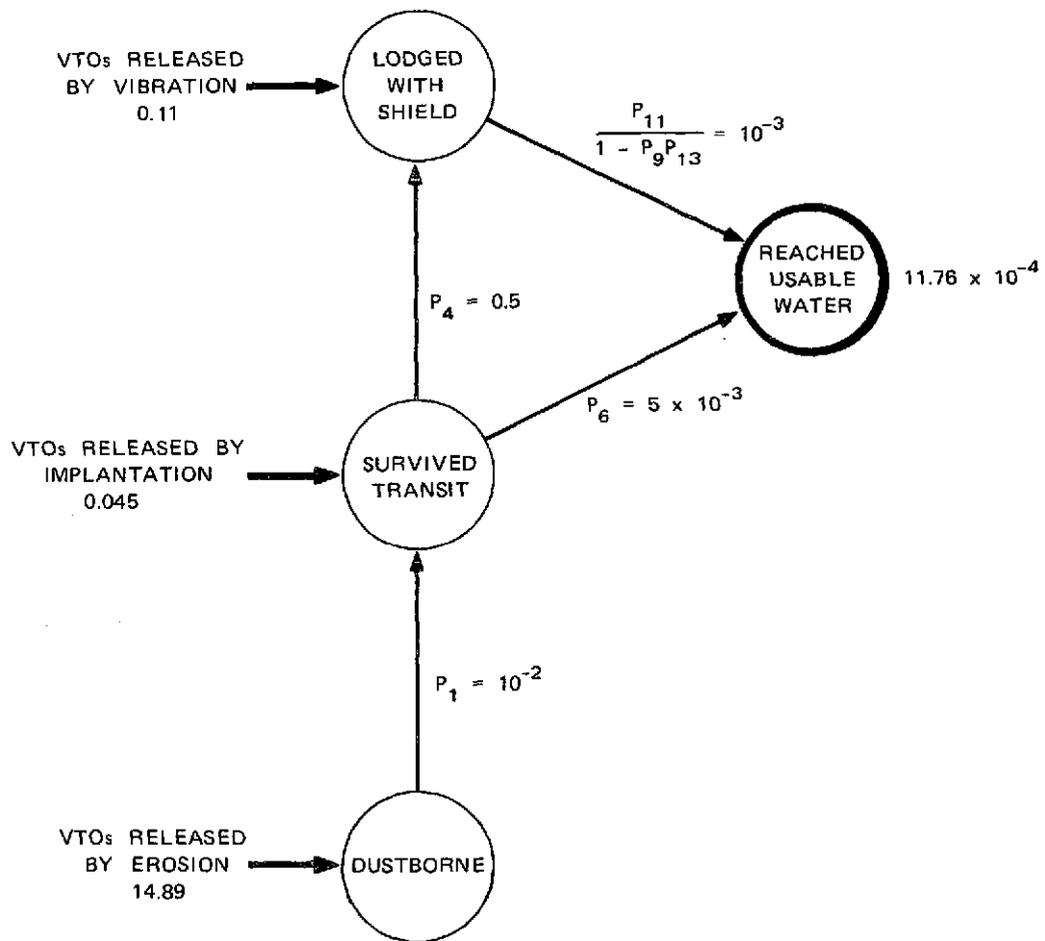


FIGURE 3.16 APPROXIMATE VERSION OF THE TRANSPORT SUBMODEL

<u>VTO Release Mechanism</u>	<u>Transport Variables</u>	<u>Probability of Reaching Usable Water</u>
Implantation	$(0.005 + 0.5 \times 10^{-3})$	$= 5.5 \times 10^{-3}$
Erosion	$0.01 \times (0.005 + 0.5 \times 10^{-3})$	$= 5.5 \times 10^{-5}$
Vibration	0.001	1.0×10^{-3}

The total expected number of VTOs reaching water is therefore approximately:

Implantation:	$0.045 \times 5.5 \times 10^{-3}$	$\approx 2.5 \times 10^{-4}$
Erosion:	$14.89 \times 5.5 \times 10^{-5}$	$\approx 8.2 \times 10^{-4}$
Vibration:	$0.11 \times 1 \times 10^{-3}$	$\approx 1.1 \times 10^{-4}$
	Total	11.8×10^{-4}

From this perspective, the most critical model variables are:

- (1) The number of VTOs released by erosion (1lrel).
- (2) The number of VTOs released by implantation (10rel).
- (3) The probability that a VTO will reach a micro-environment with usable water after transportation by a dust storm (P_6 or 2tra).
- (4) The probability that a VTO will survive transportation by a dust storm (P_1 or 1tra).

Sensitivity analyses discussed in Section 4 confirm that these are the most crucial variables.

3.3.4.2 Markov Model Computations

Exact results for the characteristics of the Transport Submodel can be obtained by using standard Markov process analysis techniques. One quantity of interest is the multistep transition probability $\varphi_{ij}(n)$, which denotes the probability of being in state j having started in state i after n cycles have passed. An

example might be the probability of a VTO that started as a "Dustborne" organism being trapped in a water microenvironment after n cycles. We could, of course, compute similar quantities for other starting and trapping states. Another quantity that will be computed is the number of cycles required to trap all but a few of those organisms entering the process.

For the sake of those computations, the six-state Markov process will be reduced to three states: the holding state "Survived Lodging" (L), and the two trapping states: "Nonviable" (N) and "Reached Usable Water" (H). The three other states of the six-state model were only useful to specify transition probabilities and input variables. The three-state model represented in Figure 3.17 is computationally much simpler.

The transition probabilities and input variables shown in Figure 3.17 have been computed from the six-state Markov model variables as follows:

$$P_H = P_{12} P_1 (P_6 + P_4 P_{10,11}) + P_{13} P_{10,11} \approx 2.8 \times 10^{-4}$$

$$P_N = P_{12} [P_{2,3} + P_1 (P_{5,7} + P_4 P_8)] + P_{13} P_8 \approx 0.5$$

$$P_L = P_9 (P_{12} P_1 P_4 + P_{13}) = 1 - P_H - P_N \approx 0.5$$

The expected number of VTOs starting in each of the three states is computed from the state occupancies of the six-state Markov model at the end of the first cycle following release. Thus, calling V_I , V_E , and V_V the expected number of VTOs released by implantation, erosion, and vibration, respectively, one obtains:

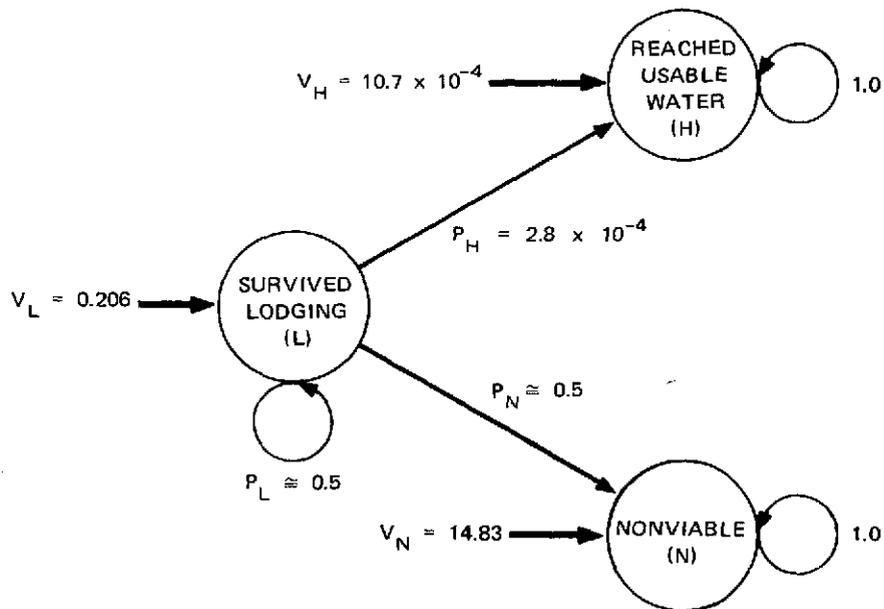


FIGURE 3.17 THREE-STATE REDUCED PROCESS SHOWING TRANSITION PROBABILITIES AND STARTING STATE OCCUPANCIES

$$V_H = (P_6 + P_4 P_{10,11}) (P_1 V_E + V_I) + P_{10,11} V_V \sim 10.7 \times 10^{-4}$$

$$V_N = P_{2,3} V_E + (P_{5,7} + P_4 P_8) (P_1 V_E + V_I) + P_8 V_V \sim 14.83$$

$$V_L = P_9 [V_V + P_4 (P_1 V_E + V_I)] \sim 0.21$$

The n-step transition matrix $\phi(n)$ of the three-state process is simply:

$$\phi(n) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{P_N}{1-P_L} & (1-P_L)^n & \frac{P_H}{1-P_L} & (1-P_L)^n & P_L^n \end{pmatrix},$$

where the rows and columns from left to right and top to bottom correspond to states "N," "H," and "L."

As n approaches infinity (the steady state), the "N" and "H" trapping states collect all the microbes, and the limiting transition probability matrix is:

$$\phi(\infty) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{P_N}{1-P_L} & \frac{P_H}{1-P_L} & 0 \end{pmatrix} .$$

Thus, the expected number of VTOs reaching a micro-environment with usable water is found to be 11.84×10^{-4} .

Another useful computation is the number of cycles or transitions, n , required before all but a small fraction, y , of organisms are trapped. Using the notation developed in Figure 3.17, this number is found to be:

$$n \geq \frac{\ln (y/V_L)}{\ln (P_L)} .$$

Thus, the number of cycles required to trap all but 10^{-4} organisms (the contamination constraint) is:

$$n \geq \frac{\ln \left(\frac{10^{-4}}{0.21} \right)}{\ln(0.5)} \approx 11 .$$

The following tabulation gives n for a few values of y :

	Values of y					
	10^{-1}	10^{-2}	10^{-4}	10^{-6}	10^{-8}	10^{-10}
n (number of cycles or transitions)	1	5	11	18	24	31

Assuming one dust storm per year, it can be seen that most released organisms are trapped after a few years on the Martian surface.

3.3.5 Transport Submodel Summary

Table 3.3 summarizes the Transport Submodel by giving the probability of reaching a microenvironment with usable water for VTOs released by implantation, erosion, and vibration.

For example, the table shows that VTOs released by implantation, although 300 times less numerous than VTOs released by erosion, have a 100 times greater chance of reaching usable water than the latter. As has been explained in this section, this is due to the relatively high exposure of VTOs released by erosion to UV radiation. Such a large difference clearly emphasizes the necessity of distinguishing between various release mechanisms and making assessments of the probability of growth conditional on the release mode of the microbe.

The output shows that a total of 11.8×10^{-4} microbes will survive transit to a microenvironment with usable water. Of these, 70 percent were released by erosion, 20 percent by implantation, and 10 percent by vibration.

The transport process has been described by a Markov model, but the results are rather insensitive to the Markovian assumption because 91 percent of the VTOs finding usable water do so during the first dust storm cycle following their release.

22

Table 3.3

TRANSPORT SUBMODEL SUMMARY

Expected Number of VTOs Released	Conditional Probability of Reaching Usable Water	Expected Number of VTOs Reaching Usable Water	Total Expected Number of VTOs Reaching Usable Water in a Viable State
Implantation 0.045	5.53×10^{-3}	2.46×10^{-4}	11.84×10^{-4}
Erosion 14.89	5.53×10^{-5}	8.23×10^{-4}	
Vibration 0.11	1.05×10^{-3}	1.16×10^{-4}	

3.4 The Reproduction Submodel

In this final component model, we examine the probability of reproduction of the viable organisms that are transported to a microenvironment with usable water.

3.4.1 Reproduction Submodel Parameters

Figure 3.18 shows three inputs to the Reproduction Submodel: (1) the expected number of VTOs that reach usable water, (2) the fraction of these organisms that are suited to the Martian environment (assuming that they are protected from UV radiation), and (3) the availability of nutrients necessary to support microbial growth and proliferation. We combine these last two inputs into a single probability that a VTO, brought by the lander, protected from UV radiation and inhabiting a microenvironment with usable water, will reproduce. Figure 3.19 shows the results of these calculations.

3.4.1.1 Resistance to Environment

The first consideration is the probability that a randomly selected VTO on the lander could reproduce in the Martian environment, assuming UV shield, water, and the existence of adequate nutrients. These spores must in particular be heat resistant, facultatively psychrophilic, facultatively anaerobic, and capable of withstanding low pressure. As mentioned earlier, this question can be addressed by experimentation in microbiology laboratories, but it has received virtually no attention until recently.

Studies have been conducted to characterize psychrophilic spore formers in the wild microbe population that might contaminate the Viking spacecraft. Surprisingly, very few of these microbes were found in soil samples from the Denver manufacturing area but significant

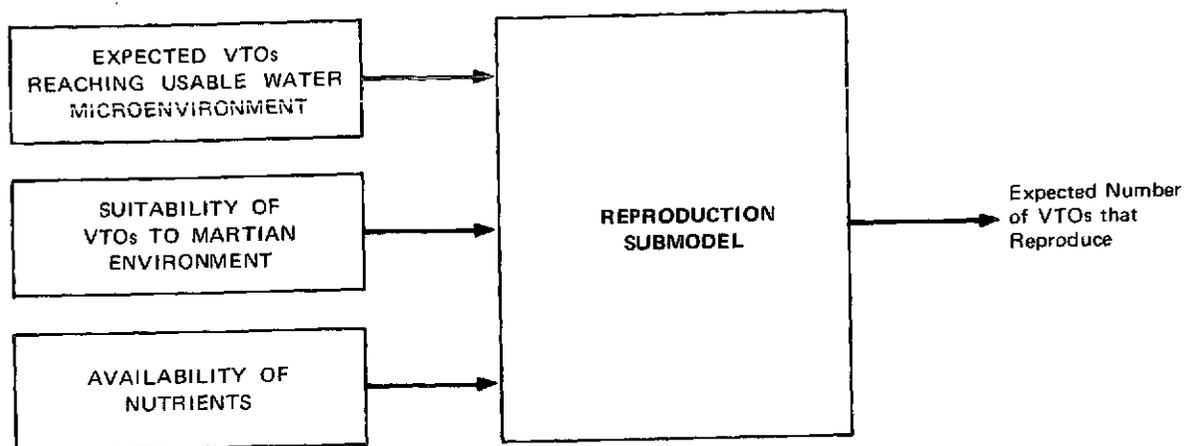


FIGURE 3.18 THE REPRODUCTION SUBMODEL

numbers were shown to exist in the soil of the assembly areas at Cape Kennedy. These microbes have been subjected to an artificial Martian environment and then incubated at 7°C to demonstrate their ability to grow at low temperatures. Bacterial counts also taken from soil samples incubated at 10°C and 0°C revealed a decrease of approximately 3 orders of magnitude in the population size at the lower temperature. Recent investigations⁴¹ have shown that among wild organisms collected at Cape Kennedy (teflon ribbon experiment), 33 bacillus isolates survived the proposed 113°C dry heat sterilization cycle. Some of the survivors were able to support a temperature of -65°C at 10⁻² torr pressure. A large proportion also demonstrated anaerobic growth after several days of incubation in the Brewer Anaerobe Jar at 24°C and with appropriate nutrients. These isolates will be subjected to artificial conditions closer to the Martian environment in the near future.

For our analysis we assumed that 5 percent of the VTOs that reach usable water and are shielded from UVs will grow and reproduce, provided they have access to necessary nutrients.

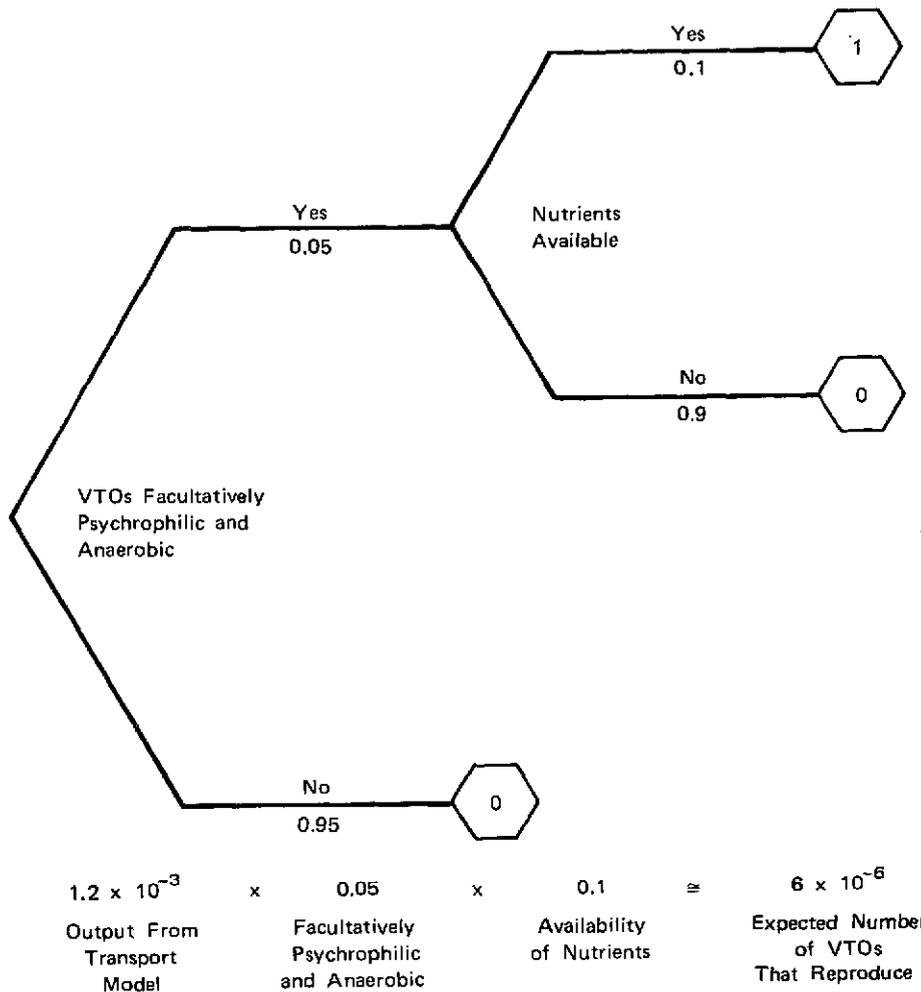


FIGURE 3.19 REPRODUCTION SUBMODEL CALCULATIONS

3.4.1.2 Availability of Nutrients

The second consideration is the availability of nutrients at locations where usable water exists. There are large uncertainties about this issue; as long as possible survivors have not been identified, we cannot specify what nutrients are necessary for microbial reproduction. Relying on expert judgment without further modeling, we have assigned 1 chance in 10 to the availability of nutrients.

3.4.2 Reproduction Submodel Summary

The joint probability that one of the surviving organisms that has reached a microenvironment with usable water and has been protected from UVs will be suited to the environment and will find the appropriate nutrients to grow and proliferate is 5×10^{-3} . This probability multiplied by the expected number of VTOs reaching water, 1.2×10^{-3} , produces the expected number of organisms that will grow on Mars: 6×10^{-6} . This number is taken to be the probability of biological contamination of the planet Mars by each of the two Viking landers.

Finally, it should be noted that both parameters of the Reproduction Submodel are of paramount importance because a change in either one will be reflected by a proportional change in the probability of contamination and both parameters are highly uncertain.

4 SENSITIVITY ANALYSIS

The purpose of this section is to measure how sensitive the assessment of the probability of contamination is to changes in modeling assumptions and value assignments. Although many experts have been consulted, the model developed in Section 3 is inevitably an approximate representation of the events leading to contamination. There are undoubtedly contamination mechanisms that have not been imagined yet, and those included in the model have necessarily been limited to keep the model tractable. Furthermore, in the present state of scientific information, many model parameters are not known with certainty. It is therefore important to know how these uncertainties affect the resulting probability of contamination and how this probability might change if some of the uncertainties were resolved. A sensitivity analysis can provide the answers. It will determine and rank the most crucial variables, i.e., the variables that, if exactly known, might cause the greatest changes in the result. These variables should then be considered candidates for further investigation.

The following exposition is intended to illustrate the methodology and provide the reader with the detailed results. Major insights from this analysis have already been explained in Section 3. In fact, sensitivity analyses were used throughout the research effort to guide development of the contamination model. The results have been gathered here for the sake of clarity and easy reference.

4.1 Model Structure and Sensitivity Analysis Methodology

The complete probability of contamination model has been given a very simple mathematical structure owing to the appropriate definition of state variables. The model can be expressed in matrix notations as:

$$P(C) = nf \text{ TRB} \quad . \quad (4.1)$$

Writing out the vectors and matrices using subscripts, the model can be expressed as:

$$P(C) = nf \sum_{i=1}^3 t_i \sum_{j=1}^4 r_{ij} b_j \quad , \quad (4.2)$$

where*

$P(C)$ = probability of contamination

$B = (b_j)$ = Bio-Burden Submodel vector, which contains the expected number of VTOs on the lander that lie on external, covered, and mated surfaces and that are encapsulated into solid material.

*Correspondence with earlier notation, as for example, Eq. (1.2):

$$P(C) = \sum_{k,i} P_{i,k}(G) E(N_{i,k})$$

Only the $k = 1$ term is retained, the fraction f of the VTOs assumed to be adapted to the Martian environment. For the i^{th} release mechanism, $i = 1, 2, 3$, nft_i is equivalent to the probability of growth $P_{i,1}(G)$. The expected number of organisms released by the i^{th} release mechanism is

$$\sum_{j=1}^4 r_{ij} b_j, \text{ equivalent to } E(N_{i,1}).$$

$R = (r_{ij})$ = Release Submodel matrix. Expresses the fraction of VTOs at each of the four locations cited above that will be released in a viable state by implantation, erosion, and vibration.

$T = (t_i)$ = Transport Submodel vector. Indicates the fraction of VTOs released by each of the three release mechanisms that will reach a microenvironment with usable water in a viable state.

f = fraction of VTOs capable of growth in a Martian microenvironment with usable water.

n = probability that necessary nutrients will be available in Martian microenvironment with usable water.

Each of the factors above depends on a number of state variables, but for each submodel--Bio-Burden, Release, Transport and Reproduction--the state variables are separate and their uncertainties may be regarded as independent. This remarkable property permits a component-by-component sensitivity analysis in the following manner:

- (1) The output variables of each component model are related to the overall probability of contamination. The corresponding relationships can be called the transfer functions of the submodels.
- (2) Analyses are performed within each component model to measure the sensitivity of output variables to changes in state variables (including input variables). The variations of the output variables are then related to the probability of contamination via the transfer functions.

Note that this approach facilitates assessment of the effect of alternative modeling assumptions. If the internal structure of one component model is modified in some way without redefining output variables, the effect of the new structure is reflected by a new transfer function and new output variables assignments. Such changes can be incorporated immediately into our model.

The Subsection 4.2 presents the submodel transfer functions. Subsection 4.3 considers component-by-component sensitivity analysis, and

subsection 4.4 reviews in detail the sensitivity analysis results for the most crucial variables.

4.2 Submodel Transfer Functions

The effect of each submodel can be summarized by the values of its parameters in Eq. (4.2). These parameters have been computed in Section 3 and the related appendices. Thus the output variables of each submodel are related to the probability of contamination in the following manner:

- Reproduction Submodel (see subsection 3.4)

$$\begin{aligned} \left(\begin{array}{l} \text{Probability of} \\ \text{contamination} \end{array} \right) &= (1/200) \times \left(\begin{array}{l} \text{number of VTOs} \\ \text{reaching usable water} \end{array} \right) \\ P(C) & \quad (nf) \quad \quad \quad (TRB) \quad (4.3) \end{aligned}$$

- Transport Submodel (see subsection 3.3)

$$\begin{aligned} \left(\begin{array}{l} \text{Number of VTOs} \\ \text{reaching usable water} \end{array} \right) &= 5.526 \times 10^{-3} \times \left(\begin{array}{l} \text{number of VTOs released} \\ \text{by implantation} \end{array} \right) \\ (TRB) & \quad (t_1) \quad \quad \quad (RB)_1 \\ &+ 5.526 \times 10^{-5} \times \left(\begin{array}{l} \text{number of VTOs released} \\ \text{by erosion} \end{array} \right) \\ & \quad (t_2) \quad \quad \quad (RB)_2 \\ &+ 1.052 \times 10^{-3} \times \left(\begin{array}{l} \text{number of VTOs released} \\ \text{by vibration} \end{array} \right) \\ & \quad (t_3) \quad \quad \quad (RB)_3 \end{aligned}$$

In other words, each implanted organism has about 5 times the chance of causing contamination as does each organism released by vibration and 100 times the chance as does each organism released by erosion. Using Eq. (4.3) above, we obtain the numerical result:

$$\begin{aligned} \left(\begin{array}{l} \text{Probability of} \\ \text{contamination} \end{array} \right) &= 2.763 \times 10^{-5} \times \left(\begin{array}{l} \text{number of VTOs released} \\ \text{by implantation} \end{array} \right) \\ &\times 2.763 \times 10^{-7} \times \left(\begin{array}{l} \text{number of VTOs released} \\ \text{by erosion} \end{array} \right) \\ & \quad \quad \quad (4.4) \end{aligned}$$

$$\times 5.260 \times 10^{-6} \times \left(\begin{array}{l} \text{number of VTOs released} \\ \text{by vibration} \end{array} \right)$$

- Release Submodel (see Subsection 3.2). The expected number of of VTOs released by each of the three release mechanisms is related to the expected number of VTOs on external, covered, and mated surfaces and encapsulated in solid materials by the following matrix multiplication:

$$\begin{array}{c} \text{Number of VTOs by} \\ \text{Released Mechanism} \\ \left(\begin{array}{l} \text{Implantation} \\ \text{Erosion} \\ \text{Vibration} \end{array} \right) \\ \text{(RB)} \end{array} = \begin{array}{c} \text{Release Probabilities} \\ \left(\begin{array}{cccc} 2 \times 10^{-3} & 10^{-4} & 10^{-4} & 10^{-6} \\ 0 & 0.8 & 10^{-2} & 10^{-4} \\ 10^{-2} & 10^{-6} & 10^{-6} & 10^{-8} \end{array} \right) \\ \text{(R)} \end{array} \begin{array}{c} \text{Number of VTOs by} \\ \text{Location Type} \\ \left(\begin{array}{l} \text{external} \\ \text{covered} \\ \text{mated} \\ \text{encapsulated} \end{array} \right) \\ \text{(B)} \end{array}$$

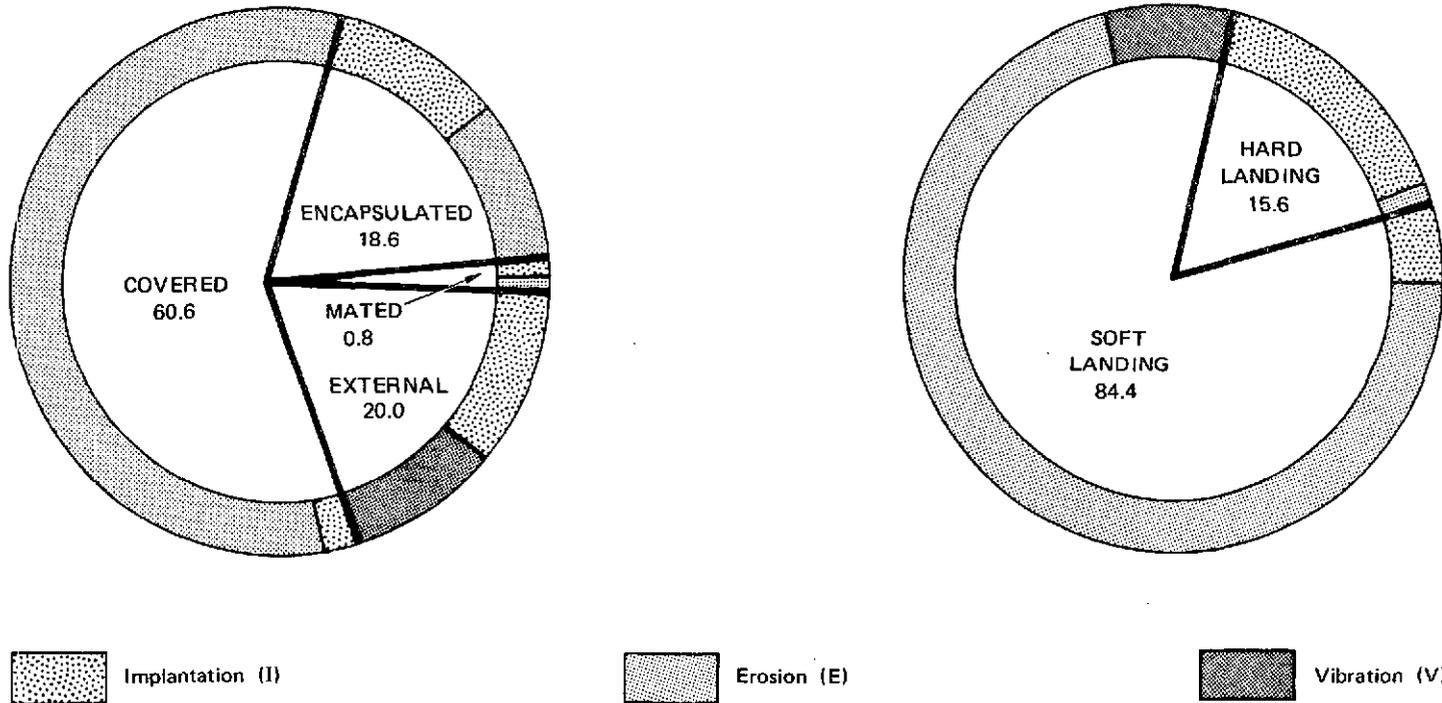
Combining the above relation with the Transport and Reproduction submodels gives:

$$\begin{array}{l} \left(\begin{array}{l} \text{Probability of} \\ \text{contamination} \end{array} \right) \\ \end{array} = \begin{array}{l} 1.077 \times 10^{-7} \times (\text{external}) \\ 2.238 \times 10^{-7} \times (\text{covered}) \\ 5.53 \times 10^{-9} \times (\text{mated}) \\ 5.53 \times 10^{-11} \times (\text{encapsulated}) \end{array} \quad (4.5)$$

which immediately shows the relative importance of the bio-burden locations: a single VTO on a covered surface has about 2, 40, and 4,000 times greater chance of contaminating Mars than does a single VTO on an external surface, a mated surface, or encapsulated in solid materials, respectively.

4.3 Sensitivity Analysis of Submodels

The preceding relations combined with Project Viking team estimates of the bio-burden by location (11 external, 16 covered, 9 mated, and 20,000 encapsulated), indicate the relative contributions of the various contamination mechanisms. These contributions by bio-burden location type and release mechanism are represented in Figure 4.1 on a percentage scale.



LOCATION OF VTOs

	COVERED	ENCAPSULATED	MATED	EXTERNAL
I =	0.8	9.3	0.4	10.3
E =	59.8	9.3	0.4	0.0
V =	0.0	0.0	0.0	9.7
TOTAL	60.6	18.6	0.8	20.0

LANDING MODE

	SOFT LANDING	HARD LANDING
I =	5.6	15.2
E =	69.1	0.4
V =	9.7	0.0
TOTAL	84.4	15.6

FIGURE 4.1 RELATIVE CONTRIBUTIONS TO THE PROBABILITY OF CONTAMINATION (PER CENT)

Interestingly, 98.3 percent of the probability of contamination can be accounted for by the contribution of five sources:

<u>Bio-Burden Location</u>	<u>Release Mechanism</u>	<u>Contribution to Contamination (percent)</u>
Covered	Erosion	59.7
External	Implantation	10.3
External	Vibration	9.7
Encapsulated	Erosion	9.3
Encapsulated	Implantation (after fracturing)	9.3
		<u>98.3</u>

The contribution from organisms on mated surfaces (0.8%) is negligible.

The next two subsections cover detailed sensitivity analyses of the Release and Transport Submodels. The most crucial variables will be pointed out; their importance will easily be justified in the light of the major contamination sources just examined.

4.3.1 Release Submodel

The Release Submodel contains 13 variables, including the 4 input variables describing the bio-burden. These variables are defined in the first column of Table 4.1. Braces denote event probabilities, that is, $\{A|B\} = 0.1$ is read as there is a 0.1 probability assigned to the event A, given that the event B has occurred. Column 3 recalls the nominal values. Columns 2 and 4 indicate low and high values used in the sensitivity analysis. Variations in the output variables are related to the probability of contamination by the Transport Submodel transfer function (see Eq. 4.4).

Table 4.1

RELEASE SUBMODEL MARGINAL SENSITIVITIES

Release Model Variables				Relative Probability of Contamination		
Parameters Being Varied		Values			Low	High
		Low	Nominal	High	Low	High
1bio, external		2.2	11	55	0.84	1.80
2bio, covered		3.2	16	80	0.52	3.42
3bio, mated		1.8	9	45	0.99	1.03
4bio, encapsulated		4,000	20,000	100,000	0.85	1.75
1rel	Hard landing	0.0004	0.002	0.01	0.88	1.62
2rel	Newly exposed hard, covered or mated	0.01	0.1	1.00	0.99	1.10
3rel	Newly exposed hard, encapsulated	10^{-4}	10^{-3}	10^{-2}	0.92	1.84
4rel	Implanted soft	10^{-4}	10^{-3}	10^{-2}	0.95	1.46
5rel	Implanted hard	0.1	0.5	1.00	0.88	1.16
6rel	VTO vibration	10^{-3}	10^{-2}	10^{-1}	0.91	1.88
7rel	VTO erosion, covered	0.1	0.8	1.00	0.48	1.15
8rel	VTO erosion, mated	10^{-3}	10^{-2}	10^{-1}	1.00	1.04
9rel	VTO erosion, encapsulated	10^{-5}	10^{-4}	10^{-3}	0.92	1.84

Note: $A|B$ indicates the probability assigned to event A given the occurrence of event B.

4.3.1.1 Marginal Sensitivity Analysis

Columns 5 and 6 of Table 4.1 reflect the relative changes in the probability of contamination when model variables are varied one at a time and the other variables are held constant at their nominal values.

Thus, seven variables appear to be critical with the extreme low and high values in the table. By order of decreasing importance they are:

- (1) The expected number of VTOs on covered surfaces of the lander (2bio).
- (2) The survivability of VTOs on external surfaces or newly exposed to the vibration release mechanism (6rel).
- (3) The survivability of encapsulated VTOs to the erosion process (9rel).
- (4) The fraction of encapsulated organisms newly exposed on hard landing (3rel).
- (5) The expected number of VTOs on external surfaces (1bio).
- (6) The expected number of VTOs encapsulated in solid materials (4bio).
- (7) The probability of a hard landing (1rel).

Note that two variables in the list are relative to the hard landing outcome even though 99.8 percent of the total number of released VTOs are liberated by aeolian erosion following a soft landing. The reasons for this apparent paradox are that a hard landing considerably increases the number of VTOs directly implanted in the Martian soil and that these VTOs are about 100 times more likely to survive and proliferate than those released by erosion.

Equally interesting is the confirmation that some variables, despite their uncertainty, play negligible roles. In particular:

- The expected number of VTOs on mated surfaces (3bio).
- The lethality of the erosion process for VTOs on mated surfaces (8rel).
- The fraction of organisms on covered or mated surfaces that are newly exposed on hard landing (2rel).

Additional information on these parameters is not likely to cause any significant change in the probability of contamination.

4.3.1.2 Joint Sensitivity Analysis

There is no apparent dependency among the critical variables of the Release Submodel except for the Bio-Burden Submodel parameters that are all affected by common sterilization procedures. However, nonlinearities of the model make it necessary to study joint sensitivities, i.e., the effect of combined variations of several parameters on the probability of contamination.

The total number of possible combinations of 13 variables is extremely large ($2^{13} - 14$), but the model structure and marginal sensitivity analyses suggest the important combinations to investigate. Two categories can be distinguished:

- (1) Combinations of marginally critical parameters.
- (2) Combinations of parameters that are not marginally sensitive by themselves but that together have a large combined effect. These parameters will be located on the same paths in the Release tree.

Table 4.2 represents the relative effect of the most critical pair of parameters. The pair is a combination of the second category above, parameters having large combined effect. Thus, two variables increasing independently the probability of contamination by a factor less than 2 are shown to increase it more than 6 times when varied jointly.

Table 4.2

MOST CRITICAL PAIR OF PARAMETERS
IN THE RELEASE SUBMODEL

External	VTO Vibration		
	10^{-3}	10^{-2}	10^{-1}
2.2	0.82	0.84	1.02
11.0	0.91	1.00	1.88
55.0	1.36	1.80	6.19

Numbers in the margins are values of the corresponding parameters: expected number of VTOs on external surfaces and the probability that a VTO will be viably released by vibration.

Numbers in the center of the table are relative probabilities of contamination.

Table 4.3 lists the eight most critical pairs. Only extreme values of the parameters are considered for their effect on the probability of contamination. The first four pairs in the list are combinations of parameters having large combined effects. The next four are combinations of marginally critical parameters. The expected number of VTOs on covered surfaces appears in all four. Pair number eight may play a more important role than indicated in the table because of the possible dependency between the expected number of covered and encapsulated VTOs.

Combinations of three or more parameters should also be studied. However, we can note that no path in the tree depends on more than five parameters and the search for crucial combinations should be limited to five parameters. Also, when the number of independent

Table 4.3

MOST CRITICAL PAIRS OF PARAMETERS AND TRIPLET
IN THE RELEASE SUBMODEL

Release Model Variables			Relative Probability of Contamination (nominal = 1.00)	
Parameters Being Varied Simultaneously	Low	High	Low	High
1. External { VTO vibration }	2.2 10^{-3}	55 10^{-1}	0.82	6.19
2. Encapsulated { Newly hard, encapsulated { exposed }	4,000 10^{-4}	100,000 10^{-2}	0.83	5.95
3. Encapsulated { VTO erosion, encapsulated }	4,000 10^{-5}	100,000 10^{-3}	0.83	5.95
4. { Hard landing { Newly hard, encapsulated { exposed }	4×10^{-4} 10^{-4}	10^{-2} 10^{-2}	0.86	5.83
5. Covered { VTO vibration }	3.2 10^{-3}	80 10^{-1}	0.43	4.30
6. Covered { Newly hard, encapsulated { exposed }	3.2 10^{-4}	80 10^{-2}	0.43	4.26
7. Covered { VTO erosion, encapsulated }	3.2 10^{-5}	80 10^{-3}	0.43	4.26
8. Covered External	3.2 2.2	80 55	0.36	4.22
9. Encapsulated { Hard landing { Newly hard, encapsulated { exposed }	4,000 4×10^{-4} 10^{-4}	100,000 10^{-2} 10^{-2}	0.78	24.90

parameters increases, the likelihood of each one having very high values decreases.

The most important triplet has been included at the bottom of Table 4.3. The combined effect of variations of the expected number of encapsulated VTOs, the probability of a hard landing, and the fraction of microbes newly exposed because of a hard landing can multiply the contamination probability by a factor of 25. The next most important triplets have a multiplicative effect of only 10.

4.3.2 Transport Submodel

The Transport Submodel is described by nine uncertain variables, including the three input variables. These variables are defined in the first column of Table 4.4. As in Table 4.2, low, nominal, and high values are indicated in Columns 2, 3, and 4.

4.3.2.1 Marginal Sensitivity Analysis

The last two columns of Table 4.4 show very clearly that, other than the input variables corresponding to the expected number of VTOs released by implantation, erosion, and vibration, only three variables are highly sensitive:

- (1) The probability of finding usable water after transport by a dust storm (P_6 or 2tra).
- (2) The probability of surviving transit in a dust storm (P_1 or 1tra).
- (3) To a lesser degree than the first two variables, the probability that water will be deposited on a VTO lodged with shield during a dust storm cycle.

These results are in accordance with the simplified but almost exact view of the transport submodel given in Figure 3.16. As seen in subsection 3.4, this representation implies that the only possible

Table 4.4

TRANSPORT SUBMODEL MARGINAL SENSITIVITIES

Transport Model Parameters				Probability of Contamination (nominal = 1.00)			
Variables Being Varied		Values			Low	High	
		Low	Nominal	High	Low	High	
Release Submodel inputs							
10rel,	implantation	0.0045	0.045	0.445	0.81	2.87	
11rel,	erosion	1.489	14.89	148.9	0.37	7.25	
12rel,	vibration	0.011	0.11	1.1	0.91	1.88	
Transport Submodel parameters							
1tra	Survive transit	(P ₁)	0.001	0.01	0.1	0.37	7.64
2tra	Find water	(P ₆)	0.0005	0.005	0.05	0.26	8.42
3tra	Find lodging	(P ₄)	0.05	0.5	0.95	0.92	1.08
4tra	Water deposition	(P ₁₁)	0.00005	0.0005	0.005	0.84	2.57
5tra	Swept aloft	(P ₁₂)	0.05	0.5	0.95	1.00	1.00
6tra	Death while lodged	(P ₈)	0.0001	0.001	0.01	1.00	1.00

transportation by a dust storm occurs when a VTO is released by erosion. This limited transport process still accounts for 99.3 percent of the probability of contamination.

4.3.2.2 Joint Sensitivity Analysis

Figure 3.16 also suggests the critical combinations of variables. These are the combinations of variables on each path to the usable water microenvironment state. Table 4.5 contains the joint effects of these combined variations. As always in the case of joint sensitivities where the variables are varied on a given set of low and high values, the effect of joint variations increases rapidly with the number of variables in each combination. At the same time, the probability of these variables having simultaneously high or low values usually becomes very small. The only exception is when the variables are positively correlated. Thus, if each of the independent variables in Table 4.5 is given, say, a 2 percent chance of exceeding its extreme high values, the high effects of pair-wise variations and triple variations will have, respectively, only 4 chances in 10^4 and 8 chances in 10^6 of occurring.

4.4 Identification of Variables Most Crucial to the Probability of Contamination

The main results from sensitivity analysis on the Release and Transport Submodels are recapitulated in Table 4.6 with the addition of the two crucial variables of the Reproduction Submodel. For each of 13 variables the table indicates 2 extreme values (low and high), 2 intermediate values (low and high), and 1 nominal value. The marginal sensitivity of the probability of contamination to the assignment

Table 4.5

TRANSPORT SUBMODEL JOINT SENSITIVITIES

Transport Model Variables			Probability of Contamination (nominal = 1.00)	
Variables Being Varied	Low	High	Low	High
1. Erosion { Survive transit } (P ₁)	1.489 0.001	148.9 0.1	0.31	73.11
2. { Survive transit } (P ₁) { Find water } (P ₆)	0.001 0.0005	0.1 0.05	0.14	69.39
3. Erosion { Find water } (P ₆)	1.489 0.0005	148.9 0.05	0.14	65.84
4. Implantation { Find water } (P ₆)	0.0045 0.0005	0.45 0.05	0.22	25.59
5. Erosion { Survive transit } (P ₁) { Find water } (P ₆)	1.489 0.001 0.0005	148.9 0.1 0.05	0.13	670.79

Table 4.6

CONTAMINATION MODEL: MARGINAL SENSITIVITY ANALYSIS

Contamination Model Variables						Probability of Contamination: (units are 10^{-6}) (nominal = 5.9)	
Parameters Being Varied	Values					Low	High
	Extreme Low	Intermediate Low	Nominal	Intermediate High	Extreme High		
Bio-Burden variables							
1bio External	2.2	5.5	11	22	55	5.0	10.7
2bio Covered	3.2	8	16	32	80	3.1	20.2
4bio Encapsulated	4,000	10,000	20,000	40,000	100,000	5.0	10.4
Release Model variables							
1rel { Hard landing }	0.0004	0.001	0.002	0.004	0.01	5.2	9.6
3rel { Newly exposed hard, encapsulated }	0.0001	0.0002	0.001	0.005	0.01	5.4	10.9
4rel { Implanted soft }	0.0001	0.0002	0.001	0.005	0.01	5.7	8.7
6rel { VTO vibration }	0.001	0.002	0.01	0.05	0.1	5.4	11.1
9rel { VTO erosion, encapsulated }	0.00001	0.00002	0.0001	0.0005	0.001	5.4	10.9
Transport Model variables							
1tra { Survive transit } (P_1)	0.001	0.002	0.01	0.05	0.1	2.2	45.2
2tra { Find water } (P_6)	0.0005	0.001	0.005	0.025	0.05	1.5	49.9
4tra { Water deposition } (P_{11})	0.00005	0.0001	0.0005	0.0025	0.005	5.0	15.2
Reproduction Model variables							
1rep { Facultative psychrophiles and anaerobes }	0.005	0.01	0.05	0.1	0.25	0.6	29.6
2rep { Nutrients }	0.01	0.02	0.1	0.2	0.5	0.6	29.6

Low and High values of the probability of contamination correspond to extreme low and high values of the variables.

of extremely low and high values to each of the input variables (the other variables being held at their nominal value) is shown in the two last columns. Intermediate values will be used later for simulation purposes.

It is very unlikely that an increase in any single state variable could cause the probability of contamination to exceed 10^{-4} . However, a combination of increases might have this effect. This possibility will be explored in two ways: by drawing from results of previous joint sensitivity analysis and by simulation (see Subsection 4.5).

From the results of joint sensitivity analysis on the Release and Transport Submodels, it is easy to identify the most likely informational changes that could cause the contamination constraint to be exceeded.

The Transport Submodel is highly sensitive to two inputs: the expected number of VTOs released by erosion and released by implantation. The Release Submodel shows that most VTOs released by erosion were located on covered surfaces. Also important to note is that originally encapsulated VTOs, newly exposed because of a hard landing, contribute to half the implanted VTOs and there are large uncertainties associated with this number.

Thus, three series of informational changes can be imagined that lead to a probability of contamination in excess of 10^{-4} :

- (1) Soft landing--As indicated in Table 4.7, if the number of VTOs on covered surfaces is twice the nominal value and if the four key variables of the Transport and Reproduction Submodels have also been underestimated by a factor of 2, the probability of contamination becomes larger than 10^{-4} .
- (2) Hard landing--A similar result is obtained if the fraction of encapsulated VTOs newly exposed because of a hard landing, the probability of a hard landing, and the number of encapsulated VTOs are larger than expected by factors of 5, 2, and 2, respectively. These circumstances

Table 4.7

THREE SERIES OF INFORMATIONAL CHANGES CAUSING THE PROBABILITY OF
CONTAMINATION TO EXCEED 10^{-4}

Variables		Case 1 (Soft Landing)	Case 2 (Hard Landing)	Case 3 Combination of Cases 1 and 2
Definition	Nominal Value			
Bio-burden Submodel				
2bio, covered	16	32	--*	32
4bio, encapsulated	20,000	--	40,000	40,000
Release Submodel				
1rel { Hard landing }	0.002	--	0.004	0.004
3rel { Newly exposed hard, encapsulated }	0.001	--	0.005	0.005
Transport Submodel				
1tra { Survive transit } (P_1)	0.01	0.02	--	0.016
2tra { Find water } (P_6)	0.005	0.01	0.01	0.008
Reproduction Submodel				
1rep { Facultative psychrophiles and anaerobes }	0.05	0.08	0.08	0.08
2rep { Nutrients }	0.1	0.2	0.2	0.16

* Dashes stand for nominal values.

greatly increase the expected number of implanted VTOs. If the probability of finding usable water and the Reproduction Submodel parameters are the same as for this first case, the probability of contamination will again exceed 10^{-4} .

- (3) Combination of the two previous series of informational changes, as shown in the last column of Table 4.7.

Detailed sensitivity analyses confirm that the eventualities just mentioned are by far the most likely to cause a violation of the contamination constraint. It is generally felt that the probability of occurrence of these or more pessimistic eventualities is on the order of 1 percent.

4.5 Simulation of the Effect of Additional Information

What is the risk that additional information about quantities in the model would lead us to revise the probability of contamination to a value in violation of the constraint? We can address this question by assigning probabilities to the values that an input quantity might have if more information were available to determine it. For example, consider the encapsulated bio-burden. We have a nominal value of 20,000 assigned to this quantity, but we do not know that this number is correct. Suppose we could find the true value. What probability would we assign to receiving the information that the encapsulated bio-burden is really 100,000 or greater? What probability would we assign that the encapsulated bio-burden is really 4,000 or less? We could assign a probability distribution on the entire range of each of the input quantities in the assessment model.

Although this process could be carried out, it is cumbersome and involves exhaustive encoding of expert judgment in the form of probability distributions. We have chosen instead to do an approximate calculation using the values in the sensitivity analysis. We make the following approximations:

- (1) The uncertainty in each of the variables is assumed to be independent.
- (2) The uncertainty in each variable is described by a discrete probability distribution, defined as follows:
 - First simulation--The nominal value is given a probability of 0.7, and the extreme values are given a total probability of 0.3 in such a way that the expected value remains equal to the nominal value.
 - Second simulation--The nominal value is given a probability of 0.5, and the remaining 0.5 probability is shared between the intermediate low and intermediate high values in such a way that the expected value remains equal to the nominal value.

Example 1: Probability Distribution for the Number of VTOs on External Surfaces (lbio)

First Simulation		Second Simulation	
Value	Probability	Value	Probability
2.2	0.250	5.5	0.333
11	0.700	11	0.500
55	0.050	22	0.167

Example 2: Fraction of Encapsulated Organisms Surviving Release by Erosion

First Simulation		Second Simulation	
Value	Probability	Value	Probability
1×10^{-5}	0.273	2×10^{-5}	0.417
1×10^{-4}	0.700	1×10^{-4}	0.500
1×10^{-3}	0.027	5×10^{-4}	0.083

Figure 4.2 shows the excess probability distributions on the risk of contamination that result from the two simulations described above. The excess probability should be interpreted as the probability that,

given the current state of information, the risk of contamination, if it could be known with certainty, would exceed a given value. Note that the horizontal scale on Figure 4.2 is logarithmic and a distribution approximately symmetrical on this scale is in fact extremely skewed. Also, the expected value of the distribution cannot be found intuitively as on a linear scale. The main statistics of the distribution are reported on Figure 4.2. In particular, there is a 1 to 2 percent chance that the mission allocation of 1×10^{-4} will be exceeded.

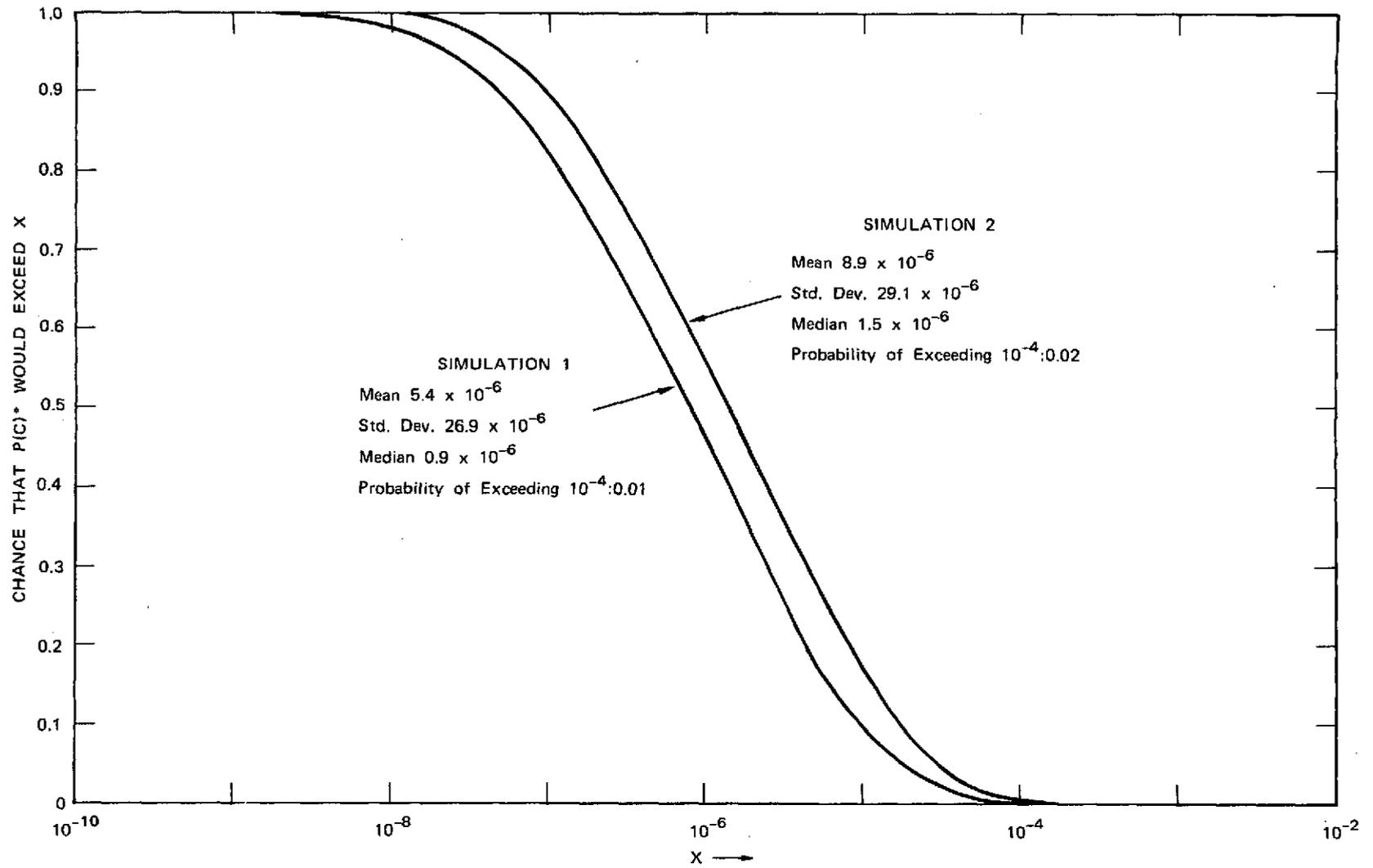


FIGURE 4.2 P(C)*, PROBABILITY OF CONTAMINATION GIVEN FURTHER INFORMATION

5 RESULTS, RATIONALE FOR NEW METHODOLOGY, AND A RECOMMENDATION

5.1 Results of the Analysis

The overall result for the probability of contamination by each Viking lander is 6×10^{-6} . This value is approximately a factor of 16 below the mission constraint imposed by NASA.

The sensitivity analysis in Section 4 shows that this result does not vary drastically when the assumptions and inputs used in the analysis are varied over a range of reasonable possibilities. However, large simultaneous changes in several input variables could cause a violation of the constraints (see Table 4.7).

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 additional information (see Figure 4.2).

This calculation indicates the need for additional investigation and research to resolve information gaps related to the contamination of Mars. Some of the information gaps can be addressed by laboratory research on earth, for example, the percentage of the poststerilization bio-burden that is facultatively anaerobic and psychrophilic. The list of sensitive

variables given in Table 4.6 may be useful as a guide to research priorities.

5.2 Rationale for New Methodology

The Sagan-Coleman approach to assessing the probability of planetary contamination is limited. Detailed information on the spectrum of microbes in the bio-burden, lethality of release mechanisms, transport mechanisms, and characteristics of potentially hospitable microenvironments on Mars should be included in the assessment. This information can be included by expanding the Sagan-Coleman approach beyond working with a single number representing the expected level of VTO release and another single number representing the probability of growth.

In this report we have shown how the detailed information now available can be structured into a model for assessing the probability of contamination. The model has been documented in this report; it should be subjected to periodic critical review by the community of scientists concerned with planetary quarantine. As new information becomes available, the model and its inputs should be suitably revised to include the new information.

We believe that the use of formal models as a basis for planning quarantine policy represents a substantial advance over NASA's current approach, which relies on the parameter $P(G)$. The detailed structural basis for assessing the probability of microbial growth permits critical examination and revision in the light of new evidence.

5.3 Recommendation

We recommend that NASA replace the current procedure of determining mission sterilization requirements on the basis of a single probability

of growth by a procedure that distinguishes among types of organisms, types of release mechanisms, and other characteristics that affect whether an individual VTO released from a spacecraft will reproduce in the environment of another planet.

Appendix A

THE SAGAN-COLEMAN FORMULA--SUMMARY AND EXCERPTS
FROM A PREVIOUS SRI REPORT

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Appendix A

THE SAGAN-COLEMAN FORMULA--SUMMARY AND EXCERPTS FROM A PREVIOUS SRI REPORT

1. Conceptual Limitations and Suggested Modifications

A model for analyzing the mission contamination problem was proposed by Sagan and Coleman.¹ This model served as the basis for discussions by the Committee on Space Research (COSPAR) that resulted in upper limits being set on the probability of contamination as a condition for space missions in the vicinity of Mars. Considerable debate and discussion of parameter values have taken place,^{42,43} but the basic structural assumptions and resulting formulas are still widely accepted by COSPAR, NASA, and NASA contractors as a means of determining sterilization requirements for Project Viking and other future unmanned planetary missions.

The basic structure, as depicted in Figure A.1, consists of a bio-release model whose output is the mean number of viable organisms released, and of a proliferation model limited to a linear relationship between the number of released organisms and the probability of contamination. Specifically:

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

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

$$E(N) = \sum_{k=0}^{\infty} k P(N = k), \text{ the expected number of organisms released.}$$

G = the event that a single released organism will survive, multiply, and contaminate a significant fraction of the planet.

The Sagan-Coleman linear approximation for the mission contamination probability is:

$$P(C) = E(N) P(G) \quad . \quad (A.1)$$

This approximation is based on two implicit and questionable assumptions. In Section 3 of this appendix we explore the implications of these assumptions in assessing the probability of planetary contamination.

If we define E_i as the event that the i^{th} released organism does not survive to multiply and cause contamination, it follows directly that:

$$\begin{aligned} P(C) &= 1 - P(E_1 \text{ and } \dots \text{ and } E_N) \\ &= 1 - \sum_{k=1}^{\infty} P(N = k) P(E_1 \text{ and } \dots \text{ and } E_k | N = k) - P(N = 0). \end{aligned} \quad (A.2)$$

If, given that k organisms are released, we assume the events E_1, E_2, \dots, E_k to be independent and of equal probability,* then:

$$P(E_1 \text{ and } \dots \text{ and } E_k | N = k) = [P(E_1 | N = k)]^k \quad . \quad (A.3)$$

* The events E_1, E_2, \dots, E_m are called independent if for all choices

$\{E_i, E_j, \dots, E_k\}$ and for all combinations $1 \leq i < j \dots \leq m$ the multiplication rule

$$P(E_i \text{ and } E_j \text{ and } \dots \text{ and } E_k) = P(E_i)P(E_j) \dots P(E_k)$$

applies.

Moreover, if we assume that the survival of any one organism is independent of the number of organisms released, then:

$$P(E_1 | N = k) = P(E_1) = 1 - P(G) \quad . \quad (A.4)$$

Substituting Eqs. (A.1) and (A.4) into Eq. (A.3) gives us

$$\begin{aligned} P(C) &= 1 - \sum_{k=0}^{\infty} P(N = k) [1 - P(G)]^k \\ &\approx 1 - \sum_{k=0}^{\infty} P(N = k) [1 - kP(G)] \\ &\approx E(N)P(G) \quad . \quad (A.5) \end{aligned}$$

The approximation is justified by the fact that $P(G)$ is very small and only moderate values of N have significant probability. This relationship is equivalent to Eq. (A.1).

Let us now consider the independence assumption underlying Eq. (A.3). The events $E_1, E_2 \dots E_k$ are clearly mutually dependent on the actual character of the Martian environment, which to a large extent is not yet known with certainty. Therefore, learning the fate of the first $k - 1$ organisms tells us something about the k^{th} organism's chances of surviving and proliferating. The significance of this informational dependence is illustrated by a more familiar problem in the following section. Fortunately, the approximation introduced by assuming independence yields a conservative estimate reasonably close to the true probability of contamination for numbers in the domain of interest.

The independence assumption underlying Eq. (A.4) dismisses the possibility that the number of released organisms depends on the landing

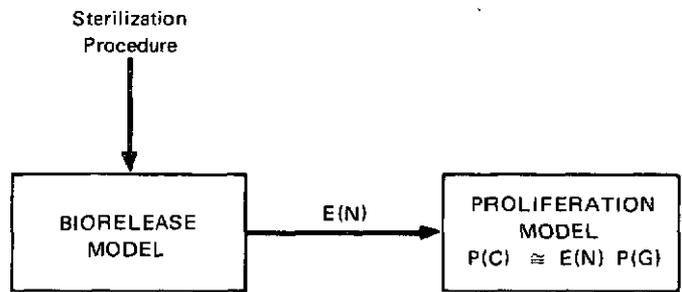


FIGURE A.1 BASIC LOGICAL STRUCTURE OF THE SAGAN-COLEMAN MODEL

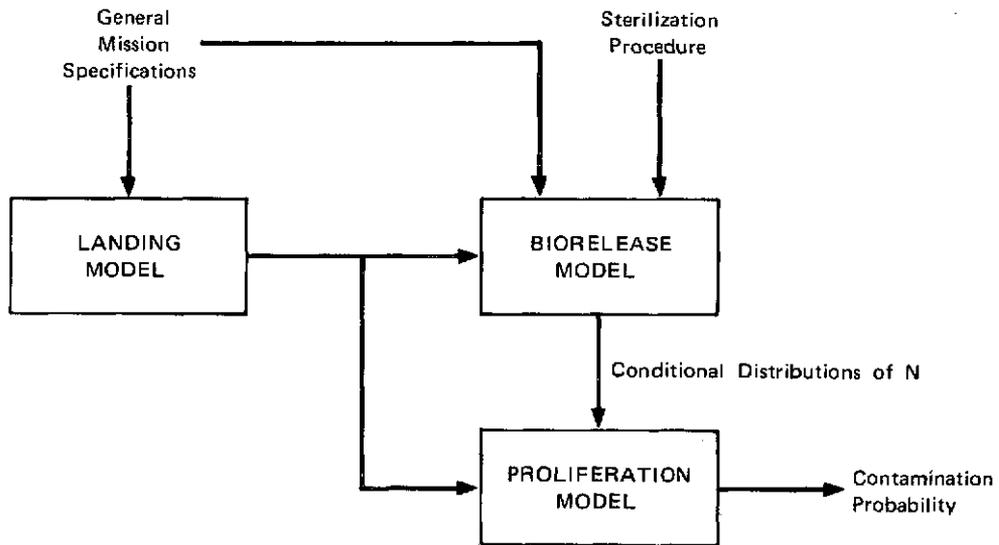


FIGURE A.2 BASIC LOGICAL STRUCTURE OF THE PROPOSED MODEL

mode, which in turn may affect survivability. In fact, a positive correlation may exist between these two factors that would yield a greater probability of contamination. Equation (A.4) is therefore inadequate, and the structure of the Sagan-Coleman model should be enriched at least to the extent shown in Figure A.2--the addition of a landing model through which the uncertainty relative to the landing mode is explicitly expressed.

2. Significance of Informational Dependence in a Series of Otherwise Identical Trials: A Classical Illustration

The following problem, which has been discussed in a slightly different form by Howard,⁴⁴ provides an example of a familiar physical process having identical but informationally dependent trials. Its significance to the mission contamination problem will be discussed shortly. Let us suppose that a tack is dropped onto a large flat surface. The tack has two possible landing positions, labeled "heads" and "tails" in the following diagram. You, the subject, are told only that the tack in the diagram is drawn to scale, that a human being will drop it from a height of four feet, and that the landing surface is very flat. Your first problem is to assess the probability of its landing on its head in 1 toss; your second problem is to assess the probability of 10 tails occurring in 10 tosses.



SKETCH A

To respond that you do not know the probabilities, never having watched any tack tossing, is unacceptable. The questions do not concern

frequencies or any other type of physical fact. We ask only a quantification of your judgment and recognize that different people will typically make different assessments. Now suppose that after much scrutiny of the diagram, you assess the probability of a head in one toss to be 0.5. Using only the rules of consistency imposed by probability theory, is it possible to deduce your response to the second question from this? The answer is no. You simply have not told us enough about your judgment (or state of information). Before any calculations can be done (on your behalf), we need to know something about how you believe the individual tosses relate to one another. To fill in this gap, you might say that you view the trials as independent, in which case we immediately have

$$P(10 \text{ tails in } 10 \text{ tosses}) = (0.5)^{10} \approx 10^{-3} .$$

But, considering the characterization of independence given earlier, does this assumption accurately reflect your state of information? It seems unlikely, for undoubtedly you would be inclined to alter your initial assessment for the probability of a head in one toss if we told you the results of the first nine tosses.

Having rejected the independence assumption, how can you compactly express the degree of dependence that you perceive to exist among the results of the separate trials? Under a very mild assumption* it can be shown that the following characterization provides all the required information. Let

f = the fraction of heads that would be observed in a very long sequence of tosses.

*The assumption is that the trials be exchangeable. For a definition and discussion of exchangeable trials see Ref. 45,

With your current state of information f can be viewed only as a random variable. What we need is your subjective (prior) probability distribution for the random variable f . This is conveniently expressed by the cumulative distribution function:

$$F(x) = P(f \leq x), \quad 0 \leq x \leq 1 \quad .$$

The mean (or expected value) of this distribution is given by:^{*}

$$E(f) = \int_0^1 [1 - F(x)] dx \quad ,$$

and consistency demands that it equal 0.5. That is, the axioms of probability theory require that your subjective probability of a head in one trial equal the mean of your subjective distribution for the fraction of heads in a great many trials.

Figures A.3 through A.5 show three possible distribution functions for the random variable f , each of which is consistent with the earlier assessment that $P(\text{head}) = 0.5$. The first of these distributions corresponds to the case of independent trials, the subject being absolutely certain that the long run fraction of heads will be 50 percent.[†] Such a distribution might be assessed by an individual who has spent the last few months tossing this same tack onto this same surface. Although he is uncertain as to what will happen in a few trials, his complete knowledge

* Integration of parts shows this formula equivalent to the usual one in terms of the density function or probability mass function.

† Of course, the subject would also view the trials as independent if he were certain that the long run fraction would be 40 percent, or any other specific number.

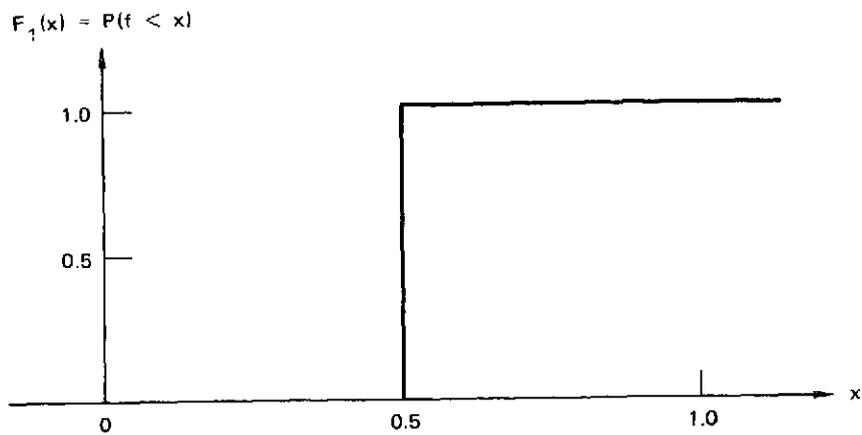


FIGURE A.3 DISTRIBUTION IMPLYING INDEPENDENT TRIALS

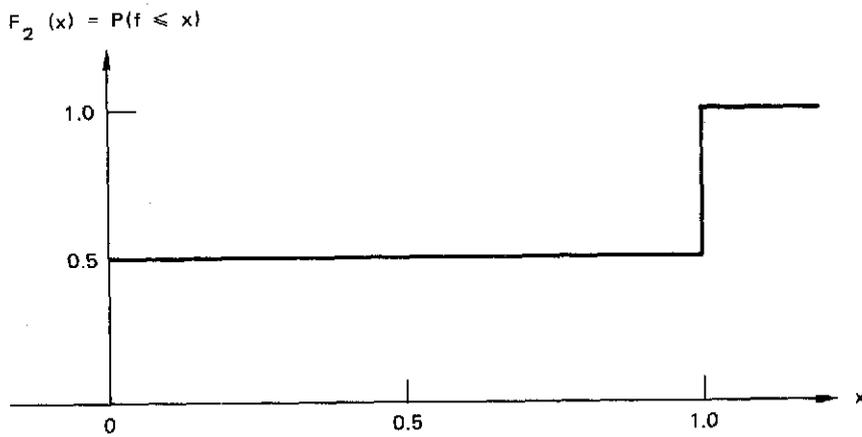


FIGURE A.4 DISTRIBUTION IMPLYING PERFECTLY DEPENDENT TRIALS

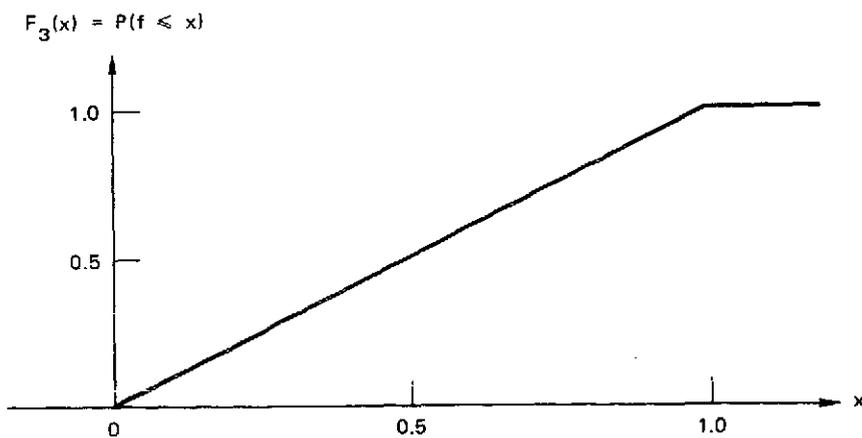


FIGURE A.5 UNIFORM DISTRIBUTION

of the basic environment leads him to view the tack as equivalent to an unbiased coin.

The second distribution (Figure A.4) corresponds to the case of totally dependent trials. The subject is absolutely certain that the tack will always come up either heads or tails, but he is not sure which. (He might have an acquaintance who has tossed the tack many times and told him it always falls one way, but left him to guess which way.) He has assessed the probability of all heads to be 0.5 and that of all tails to be 0.5. Note that if this subject were able to observe one toss, it would resolve all his uncertainty about the outcomes of subsequent tosses.

The type of distribution that we would generally expect, intermediate to the preceding extreme cases, is shown in Figure A.5. Here the subject reveals great uncertainty about the experiment's environment and assigns a uniform distribution over the interval of possible values. The mean of his distribution, like that of the others, is $E(F) = 0.5$.

Given the probability distribution for f , we can calculate the probability of all tails in n trials using the formula*

$$P(\text{all tails in } n \text{ trials}) = E \left[(1 - f)^n \right] \quad n \leq 1 \quad . \quad (\text{A.6})$$

From this we have computed the relationships shown in Figure A.6 for each distribution discussed earlier. The subject who views the trials as independent thinks it very unlikely (less than 1 chance in 1,000) that he would not observe a head in the 10 trials. In contrast, the subject who views the trials as perfectly dependent continues to assign a probability of 0.5 to the event of all tails, regardless of how many times the tack will be tossed. The corresponding relationship for a third subject lies between these two extremes. In particular, the third

* This is an application of de Finetti's theorem.⁴⁵

subject assesses the probability of 10 tails in 10 trials to be about 0.09, 100 times the probability implied by the first distribution. Thus, we find that the three individuals differ greatly in their assessment of what is likely to occur in repeated trials, although they agree perfectly about the probability of a head in a single trial. It is the degree of informational dependence among trials that differs among subjects, and these differences have significant implications.

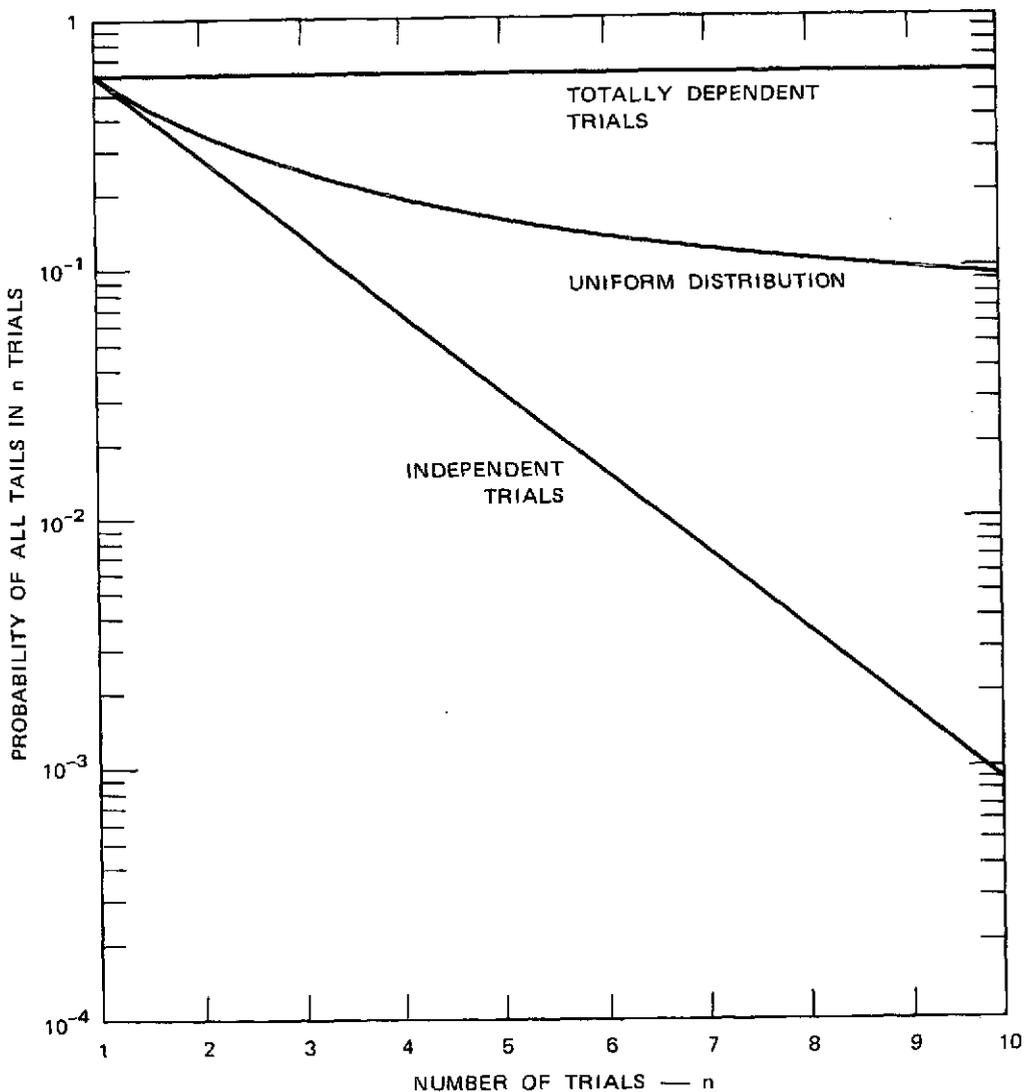


FIGURE A.6 PROBABILITY OF ALL TAILS VERSUS NUMBER OF TRIALS

3. Application of Informational Dependence to the Contamination Problem

A parallel between the preceding illustration and the contamination problem can be drawn by associating the event "tail" on the i^{th} toss with the Event E_i previously defined as "the i^{th} released organism does not survive to multiply and cause contamination." Let us also rename f as the fraction of a great many released organisms that would survive and reproduce (a random variable). Then, given that k organisms are released and that events E_1, E_2, \dots, E_k are exchangeable, Eqs. (A.2) and (A.6) yield:

$$P(C) = 1 - E \left[(1 - f)^k \right] \quad . \quad (A.7)$$

The degree of dependence that is perceived to exist among all events E_i can be completely described by a prior probability distribution for the random variable f . A possible distribution is shown in Figures A.7 and A.8. The expected value of f is 10^{-5} and its variance is 3.7×10^{-8} . A typical value of k might be 10. Taking a series expansion of Eq. (A.7),

$$\begin{aligned} P(C) &= 1 - E \left[1 - kf + (1/2)k(k-1)f^2 - \dots \right] \\ &= kE(f) - (1/2)k(k-1) E(f^2) + \dots \quad , \end{aligned}$$

and applying the illustrative values of k and f defined above, we verify that the series converges rapidly:

$$P(C) \sim 10^{-4} - 1.7 \times 10^{-6} + \dots \quad .$$

More generally, it can be demonstrated that the first-order approximation

$$Q(C) = k E(f) \quad (A.8)$$

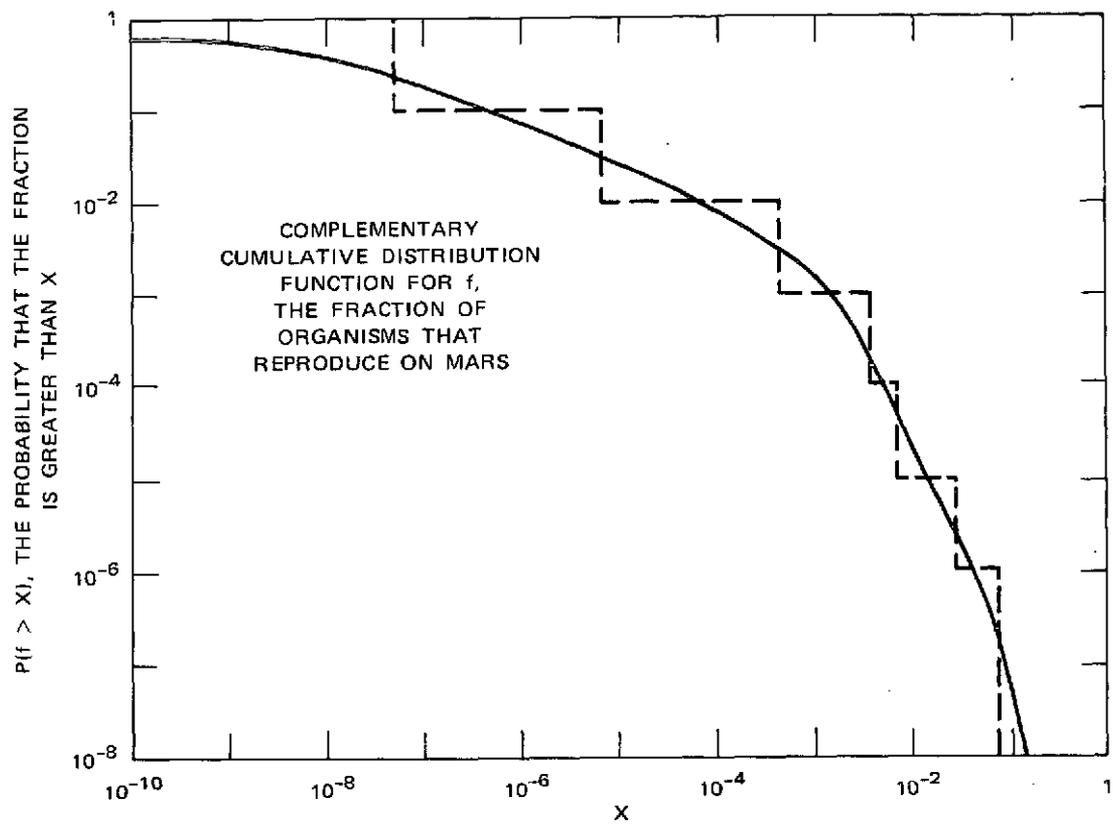


FIGURE A.7 ILLUSTRATIVE PROBABILITY DISTRIBUTION FOR FRACTION OF ORGANISMS ACHIEVING GROWTH
(Adapted from previous SRI report².)

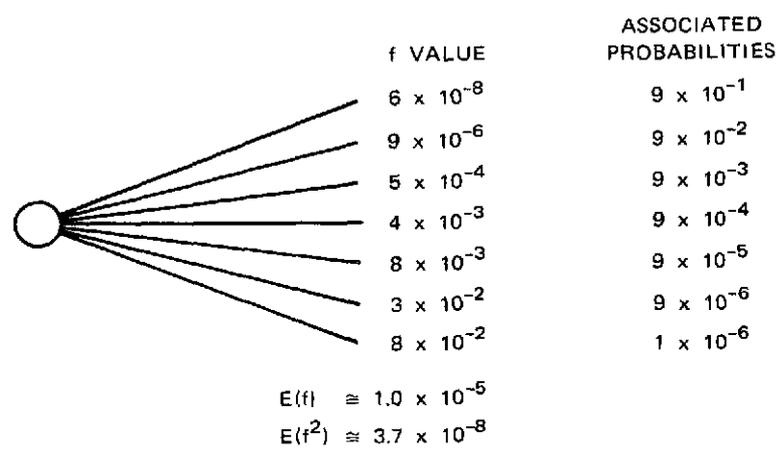


FIGURE A.8 DISCRETE APPROXIMATION FOR GROWTH DISTRIBUTION
(Adapted from previous SRI report².)

is always an upper (conservative) estimate of the probability of contamination and is bounded according to the relation:

$$Q(C) \geq P(C) \geq Q(C) - B \quad , \quad (A.9)$$

where

$$B = (1/2)k^2 E(f^2) \quad . \quad (A.10)$$

Furthermore, if, under the same conditions, the fraction of released organisms that would survive and proliferate is independent of the total number N of organisms released, $Q(C)$ reduces to

$$Q(C) \simeq E(N) E(f) \quad , \quad (A.11)$$

which is identical to the Sagan-Coleman formula with $E(f) = P(G)$. The error bound B becomes

$$\begin{aligned} B &= (1/2)E(N^2) E(f^2) \\ &= (1/2) \left\{ \left[E(N) \right]^2 + \text{Var}(N) \right\} \left\{ \left[E(f) \right]^2 + \text{Var}(f) \right\} \quad . \quad (A.12) \end{aligned}$$

Approximation (A.11) is therefore a reasonably conservative estimate of the probability of contamination under these circumstances except for pathological cases where both the probability of contamination and the variances of N and f are large, in which case it becomes overly conservative, with $Q(C) \gg P(C)$. For example, assume that all released organisms survive and reproduce with probability 10^{-5} , or all of the organisms die with probability $1 - 10^{-5}$. Assume also that 100 organisms will be released, with probability 0.10, or that none will be released. The expected values of these two variables have remained unchanged and

$Q(C) = 10 \times 10^{-5} = 10^{-4}$ as before. However, it is clear that under the conditions assumed, the overall probability of contamination would be only $P(C) = 10^{-1} \times 10^{-5} = 10^{-6}$.

If, on the contrary, the fraction of released organisms that would survive and proliferate and the total number of organisms released are dependent through a common factor such as the landing outcome, the probability of contamination is no longer equal to the product of the expected values $E(N)$ and $E(f)$ but, with a minor modification to Eq. (A.11), can be computed directly from the joint distribution of N and f conditional on the common factor, i.e.,

$$Q(C) = \sum_i P(A_i) E(N_i) E(f_i) \quad (A.13)$$

with

- A_i = the i^{th} landing outcome (hard landing; soft landing).
- $E(N_i)$ = the expected number of organisms released conditional on the occurrence of A_i .
- $E(f_i)$ = the expected fraction of released organisms that would survive and reproduce conditional on the occurrence of A_i .

This modification is incorporated in the Release Submodel described in the main body of this report.

Appendix B

RELEASE SUBMODEL PROBABILITY ASSIGNMENTS

Appendix B

RELEASE SUBMODEL PROBABILITY ASSIGNMENTS

Figure B.1, a duplicate of Figure 3.7, shows the probability assignments used in the Release Submodel. The numbers shown in circles are expected bioloads as computed in the Bio-Burden Submodel. Also in Figures B.1 and B.2 are references to the model variables described below:

- 1rel--The probability of a hard landing is 0.002.*
- 2rel--The fraction of organisms newly exposed on hard landing.
- 3rel--Parameter "a" in Figure B.2 was estimated by the authors to be 0.1, 0.1, and 10^{-3} , respectively for covered, mated, and encapsulated locations. The fraction newly exposed is based on fracture ratios and can be computed by the following equation (assuming uniform distribution of organisms in the given location):

$$f_{ne}(\text{location}) = \frac{A_1(\text{location}) - A_0(\text{location})}{V(\text{location})}$$

where

$A_1(\cdot)$ is the surface area of type (\cdot) after fracturing

$A_0(\cdot)$ is the original surface area of type (\cdot)

$V(\cdot)$ is the volume (or integrated surface area) of type (\cdot)

(The role of parameter "a" is explained in Figure B.2.)

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* See p. 21 of Reference 11.

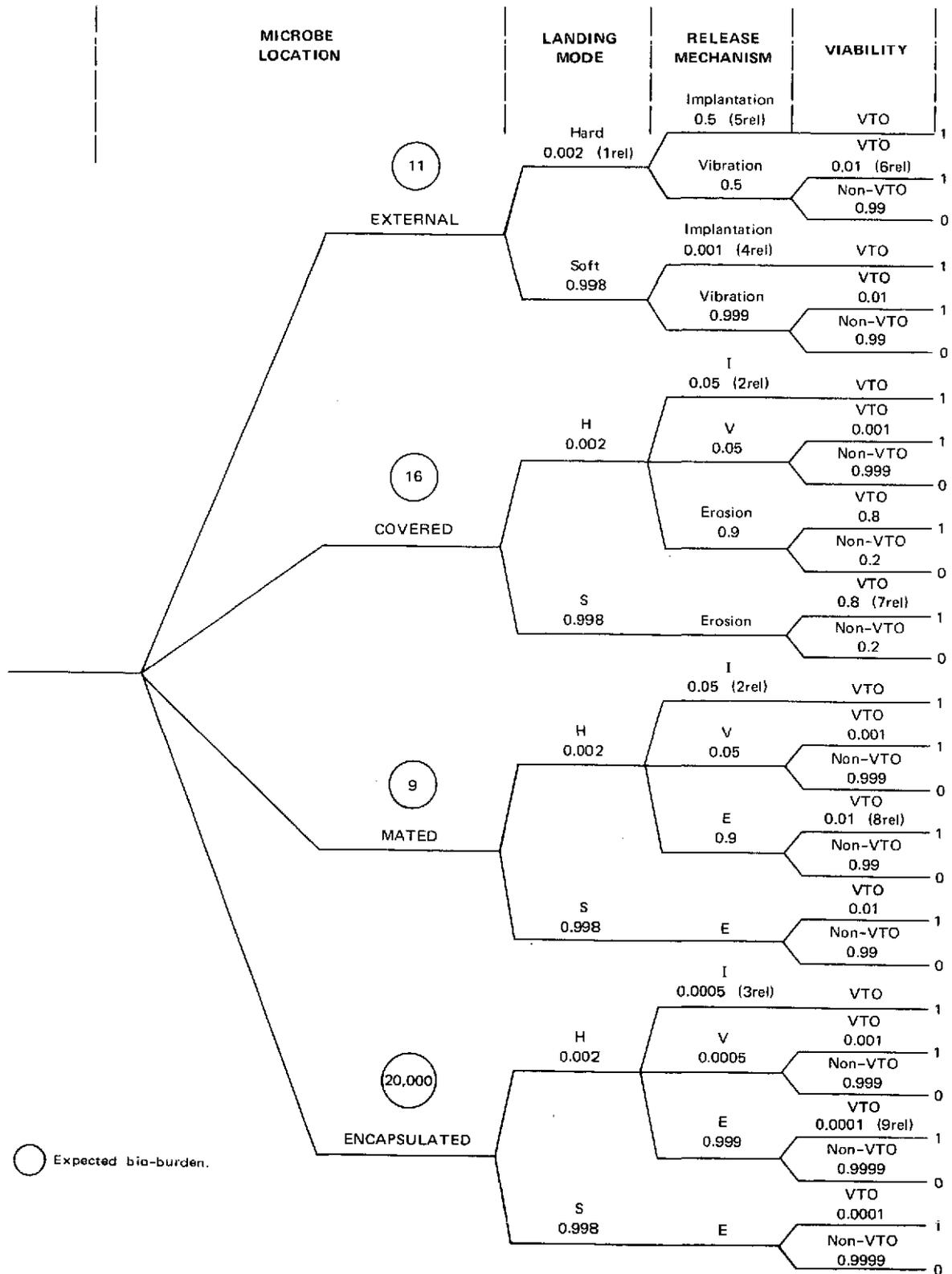


FIGURE B.1 TREE FOR VTO RELEASE: PARAMETERS

MICROBE LOCATION	a $f_{ne}(\cdot)$ - fraction newly exposed	b portion of f_{ne} Implanted	c fraction surviving Vibration	d fraction surviving Erosion
EXTERNAL OR NEWLY EXPOSED	1.0	0.5 (5rel)	10^{-2} (6rel)	No erosion
COVERED	0.1 (2rel)	—	—	0.8 (7rel)
MATED	0.1 (2rel)	—	—	10^{-2} (8rel)
ENCAPSULATED	10^{-3} (3rel)	—	—	10^{-4} (9rel)

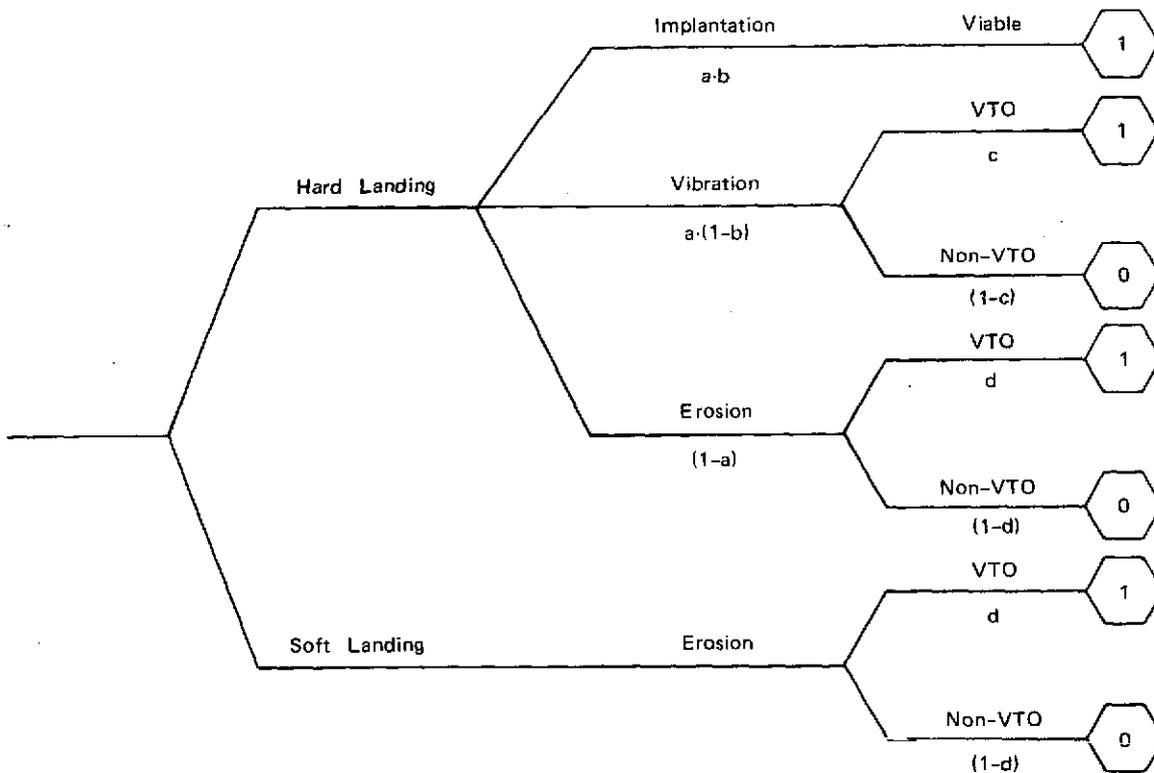
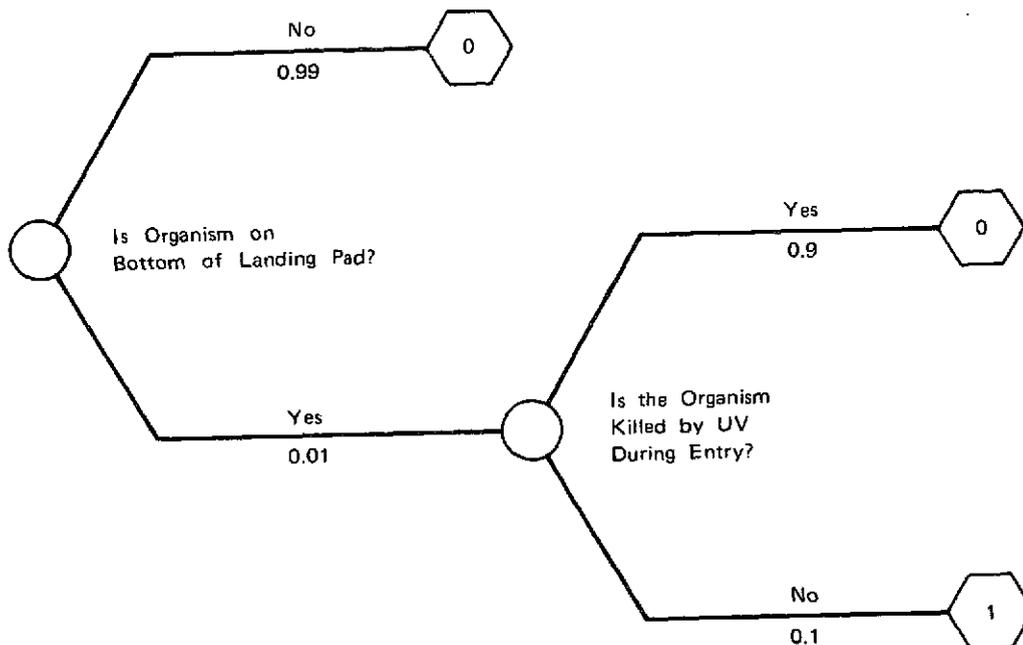


FIGURE B.2 RELEASE SUBMODEL PARAMETERS

4rel--The fraction of organisms implanted on a soft landing is assigned by the authors, using the following tree.



SKETCH B

5rel--The fraction of external or newly exposed organisms that are implanted on hard landing is assigned by the authors to be 0.5. The role of this probability is explained in Figure B.2, where it has been renamed "b."

6rel--The fraction of VTOs on external surfaces or newly exposed that survive release by vibration is assigned by the authors to be 10^{-2} . This number can be justified as follows. First, the microbe is not buried in dust; otherwise, it would be considered on the implanted branch. Secondly, it is most likely exposed to the sterilizing UV flux, which is fatal for all microbes after a period of hours. Therefore, the only surviving organisms on external surfaces are those shielded or shaded from direct and reflected radiation. We assume the fraction of external surface area meeting this criterion is 10^{-2} . The role of this probability is explained in Figure B.2, where it has been renamed "c."

7rel--The probability of VTOs on covered surfaces surviving release by erosion was assigned as 0.8 by the authors. We assume the release is from a "black box," of which a "corner" has been eroded away. The volume of the box near the corner (we assume 20 percent) is exposed to

the lethal soil abrasion process and the remainder is not. Thus we give the microbe an 80 percent chance of survival. (NASA specifications range from 10^{-2} to 1.0.)⁸

8rel--The fraction of VTOs on mated surfaces surviving release by erosion is assigned as 10^{-2} for reasons similar to those in the previous note. (The NASA specification is 10^{-3} .)⁸

9rel--We understand from Exotech that this probability of encapsulated organisms surviving erosion is based on work at Boeing (supervised by the Jet Propulsion Laboratory) and has been assigned a value of 10^{-4} .³⁶ The role of the three variables above is explained in Figure B.2, where they have been renamed "d."

Appendix C

TRANSPORT SUBMODEL PROBABILITY ASSIGNMENTS

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Appendix C

TRANSPORT SUBMODEL PROBABILITY ASSIGNMENTS

Figure C.1 is a duplicate of Figure 3.12 and is used as a reference to identify the various transitions of the six-state Markov Transport model. Transition probability assignments are discussed below in the order of their numbering. (Transition i is represented by transition probability P_i .)

P_1 Survive Transit (ltra)

Ultraviolet radiation of the intensity found on the Martian surface is normally considered lethal to microorganisms after an exposure time of a few minutes. The fraction of *B. Subtilis* spores surviving after an exposure of t minutes can be approximated by the following formula:

$$f_s = e^{-Iat} \quad , \quad (C.1)$$

which fits a curve in Hollaender's⁴⁷ Figure 2-8. "I" is the UV flux: 20 ergs/sec/mm² (approximately 0.2 W/sq ft). "a" is a constant with a value of 23 (computed to fit Hollaender's curve). Using this relationship, we can compute the fraction surviving this nominal UV flux for several values of t , as shown in Table C.1. Other spores may be more or less resistant to UV flux but not in a proportion that could change significantly the above results.

Attenuation of UV flux during dust storms is insufficient to protect unshielded terrestrial organisms for much longer time periods. The fraction of the UV flux received on the Martian surface during a dust storm can be approximated by:

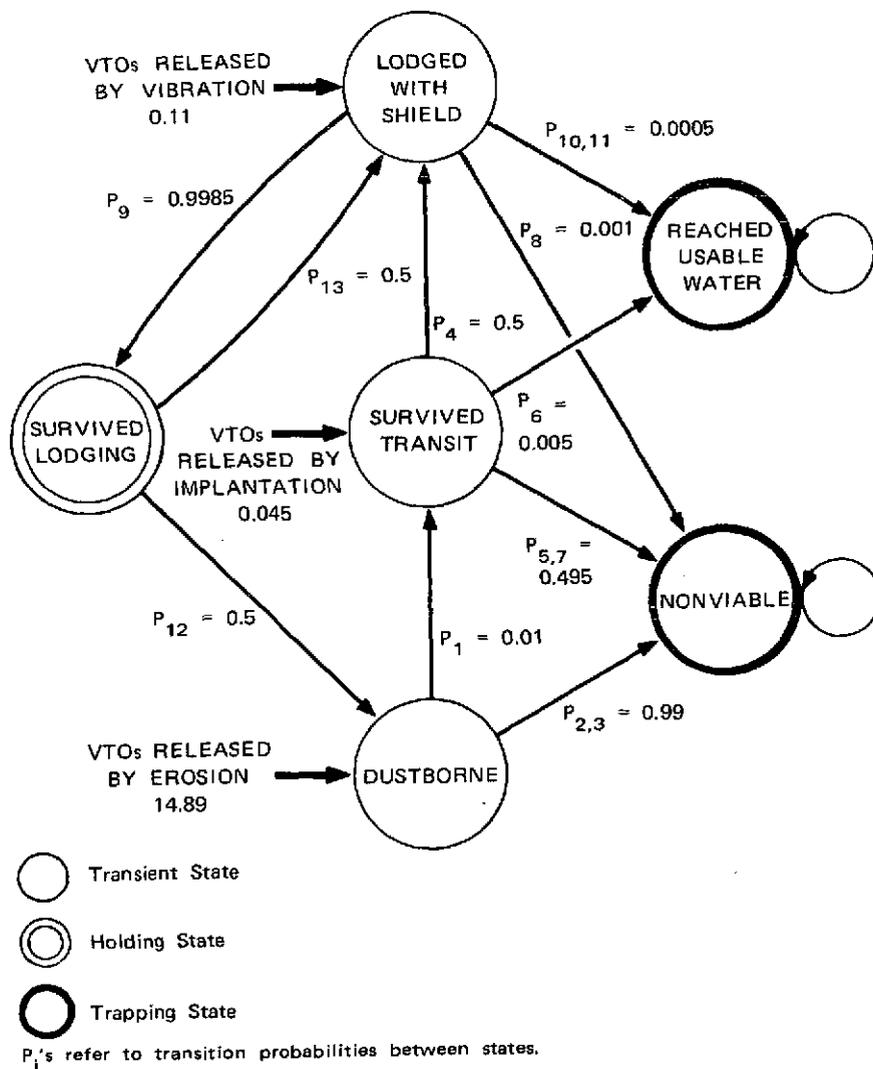


FIGURE C.1 TRANSPORT MARKOV MODEL: PROBABILITY ASSIGNMENTS

Table C.1

FRACTION OF SPORES SURVIVING 2×10^3 erg/sec/cm² FLUX

	Values of τ (minutes)		
	1	10	100
$f_s(t)$	10^{-2}	10^{-20}	10^{-200}

$$f_t = e^{-\tau/\mu} \quad . \quad (C.2)$$

Equation (C.2) states that the fraction of UV radiation transmitted from above the "atmosphere" to the surface (f_t) is approximated by an exponential involving the optical thickness (τ) and the cosine of the angle between a normal to the surface and the sun (μ). In a paper summarizing values of " τ " from Mariner IX data, Pang⁴⁶ shows that during the 1970 November-December global dust storm the value of τ ranged from 0.5 to 0.9. Using Eq. (C.2) we compute values of f_t , assuming $\mu = 1$. (See Table C.2.)

Table C.2

FRACTION OF UV FLUX TRANSMITTED TO THE SURFACE
AS A FUNCTION OF DUST STORM OPTICAL THICKNESS

	Normal Condition	Dust Storm	Heavy Dust Storm	Massive Dust Storm
τ	0.3	0.8	1.3	1.8
$f_t(\tau)$	0.74	0.45	0.27	0.16

Note that even with $\tau = 1.8$ (a value much higher than Pang's data indicate) the flux attenuation is less than an order of magnitude. Revising Table C.1 by using an optical thickness of 1.8 yields the data in Table C.3.

Table C.3

FRACTION OF SPORES SURVIVING
ATTENUATED UV FLUX

	Values of t (minutes)		
	1	10	100
$f_s(t)$	0.38	4×10^{-5}	10^{-44}

Exposures on the order of tens of minutes to a few hours (depending on sun angle) even during dust storms seem therefore to be lethal to all unshielded organisms.

We are thus left to consider the microbes that do find shielding. These would most likely be in spore colonies or as individual spores attached in a shielded manner to some landed or indigenous particle. We assign the probability of an organism finding such a shield as 10^{-2} . Note that Hagen et al.²¹ observed reductions of two orders of magnitude over a period of several weeks in populations of *B. Cereus* and *B. Subtilis* airborne in simulated Martian dust cloud.

P_{2,3} Death During Transit

Two mechanisms may render microbes nonviable while in transit: UV radiation (2) and soil abrasion (3). We believe that UV radiation dominates abrasion for unshielded organisms and that abrasion has an

insignificant effect on shielded organisms. Thus we compute the transition probability $P_{2,3}$ as the complement of probability P_1 :

$$P_{2,3} = 1.0 - 0.01 = 0.99 \quad .$$

P_4 Find Lodging with Shield (3tra)

To be in a position to take transition number four, the organism must have survived the transport process. Given this survival, two inferences are likely:

- The microbe is in a colony that was transported.
- The microbe is otherwise shielded by some mass to which it is attached.

The question now is "How can this organism find a home that will provide lodging and UV shielding until the next storm?" Indeed, the only lodging that it need find is that which will be sufficient for the additional order of magnitude in UV flux during non-storm periods. Conditioned on the fact that the organism has survived thus far, we assume it is a 50/50 proposition and that it will be able to find the additional shielding.

P_5 Permanently Lodged

We treat Transitions 5 and 7 as the same. Transition 5 refers to an organism becoming permanently lodged without water after any storm. We will exclude from our definition of "permanent lodging" the event of water being deposited on this organism. Thus we can treat a permanently lodged microbe as one that is nonviable. See Transition P_7 .

Table C.4 contains a list of possible existence mechanisms for water in a usable form on Mars. Most terrestrial organisms require water in a liquid form to proliferate; however, some organisms are known to live on water vapor at sufficiently high partial pressure, or on ice at temperatures greater than -10° C, or on water contained in nutrients or bound in some form. Because of the triple point problem, we need a water source, elevated pressure, and heat to create a liquid for any period of time. Of the mechanisms listed in Table C.4, one of the most likely has been proposed by C. B. Farmer¹⁹ of the Jet Propulsion Laboratory. Briefly, the theory is that ice at a depth of 1 cm below the surface is melted by solar radiation. If the ice is covered by 1 cm of small dust particles, then the diffusion of water vapor from the "melted" ice up through the dust layer may be sufficiently retarded to assume liquid phase "water" under the dust for some period of time. Farmer's calculations show that the duration of water in the liquid phase could be on the order of hours. He estimates³⁹ that 1 percent of the surface could have the above combination of factors. If we assume that their existence is uniformly distributed over the Martian surface, then we can say the organism would have a 1 percent chance of finding a water environment after any transport by the winds. We need to temper this assignment by an estimation of the probability that this entire mechanism does "work" on the surface. We have assigned a probability 0.25 to the existence of this mechanism.

An alternative mechanism has been proposed by A. P. Ingersoll.³⁹ His model suggests liquid phase water is limited to concentrated solutions of strongly deliquescent salts. After informal discussions with him, we assess that the fraction of the surface amenable to liquid water is again roughly 1 percent and the probability of existence of this mechanism is 0.25.

Table C.4

WATER EXISTENCE MECHANISMS

Model	Source of			Probability of Existence	Fraction of Surface* Where Water Is Usable	P ₆
	H ₂ O	Pressure	Heat			
C. B. Farmer	Ice	Dust	Solar radiation	0.25	0.01	0.0025
A. P. Ingersoll	Ice	Salt pools	Solar radiation	0.25	0.01	0.0025
"Black Rock"	Ice	Ice pocket	Solar radiation	10 ⁻²	10 ⁻⁴	10 ⁻⁶
Bound H ₂ O	Bound	--	--	10 ⁻¹	polar cap fringe: 10 ⁻² 10 ⁻⁵	10 ⁻⁶
Polar Ice	Polar	Low elevation	Geothermal	10 ⁻⁴	10 ⁻⁴	10 ⁻⁸
Geothermal (M. H. Carr)	Permafrost	Subsurface	Geothermal	10 ⁻²	10 ⁻⁷	10 ⁻⁹
Morning Dew	Dew	Low elevation	Solar	10 ^{-8†}	10 ⁻⁴	10 ⁻¹²
Meteor Impact	Ice	Subsurface	Meteor	10 ^{-6†}	10 ⁻⁶	10 ⁻¹²

* Assume uniform distribution unless otherwise noted.

† Includes penetration probability.

Looking again at Table C.4, we see that all the other mechanisms have a value for Transition P_6 (assigned by the authors) that is much lower than the first two. We will therefore ignore the others and compute Transition P_6 using only the Farmer and Ingersoll models. The computation is as follows:

$$P_6 = P_{6F} + P_{6I} - P_{6FI} \quad (C.3)$$

Here P_{6F} refers to the probability found in the last column of the "Farmer" row in Table C.4. Similarly, P_{6I} is the "Ingersoll" probability. The last term in Eq. (C.3) is the joint probability that an organism finds water from both sources in the same spot. Because of the dissimilarity between the two "liquid" water sources, the authors would assign a value for P_{6FI} at least an order of magnitude lower than 10^{-3} , which for practical purposes we call zero.

Thus,

$$P_6 = 0.0025 + 0.0025 - 0 = 5 \times 10^{-3} .$$

Sensitivity analysis will show that this number and the probability of surviving UV flux during transit are the two most critical parameters of the Transport Submodel.

Possible water encounters other than those listed in Table C.4 are described by Transition 11.

P_7 Death Given Transport Survival

Transition 7 is computed with Transition 5 as being the complement of Transitions 4 and 6:

$$P_{5,7} = 1.0 - (P_4 + P_6) .$$

P₈ Death While Lodged with Shield (6tra)

Death here could be caused by temperature cycling or some environmental factor other than UV radiation. A difficulty with the assessment of Transition 11 is that it depends on the definition of the dust storm cycle and therefore on the definition of what constitutes a dust storm. As will be seen below, Transition 12 can be interpreted as definition of a dust storm: an event that has a 50/50 chance of sweeping a lodged microbe aloft. Transition 8 is assessed by the authors to be 500 times less likely than Transition 12, that is, the microbe has a 0.002 probability of being killed before being picked up by the next storm. Transition 8 has therefore a probability of 10^{-3} in the nominal case ($P_{12} = 0.5$).

P₉ Survive Lodging

Survived lodging is a complement of Transitions 8, 10, and 11:

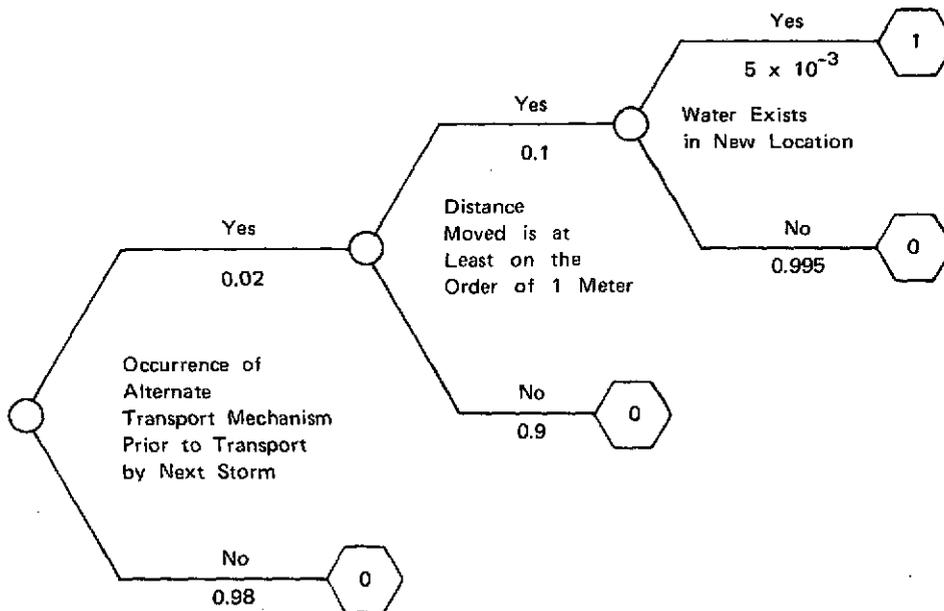
$$P_9 = 1.0 - (P_8 + P_{10} + P_{11}) \quad .$$

P₁₀ Alternate Transport Mechanism

Probability 10 refers to the existence of an alternate transport mechanism: vibration, earthquakes, and the like. We model the question as shown in Sketch C. Taking the expectation, we find $P_{10}/P_{12} = 10^{-5}$ or $P_{10} = 5 \times 10^{-6}$.

P₁₁ Water Deposition on Organism (4tra)

Assuming it survives the transport process, an organism is most likely to be left in a dry location. However, there may well be a rare event that would cause usable water to be deposited at the microbe's site. Transition 11 accounts for this event.



SKETCH C

This rare event is to be distinguished from those events in Transition 6. If, for instance, an organism lands in a spot that is initially dry but will produce water by one of the methods in Table C.4 at some time during the microbe's stay, we consider this event to be part of Transition 6. On the other hand, if water were deposited by some means not explained in Table C.4, we would want to consider it as part of Transition 11.

Transition 11 is defined as rare compared with Transition 6, which equals 5×10^{-3} . The authors assign Transition 11 as equal to 5×10^{-4} , that is, 10 times less probable than Transition 6 and two times less probable than Transition 8, death while lodged with shield. In other words, the probability that usable water will be deposited on a VIO lodged with shield by some other means than described in Table C.4 and prior to transport by the next dust storm is equal to 10^{-3} .

Transition P_{10} becomes negligible compared with P_{11} .

P₁₂ Swept Aloft by the Next Dust Storm (5tra)

We assign 0.5 to the probability that VTOs lodged with shield in any location will be swept aloft by the next dust storm. This probability alternatively defines the magnitude of Martian winds that qualify as dust storms. The output of the model is very insensitive to this number since most VTOs reach usable water during the first dust storm cycle.

P₁₃ Stay Lodged

Transition 13 is the complement of Transition 12: the fraction of VTOs not picked up by the next storm but eventually available for transport at a later period. That is, $P_{13} = 1.0 - P_{12}$.

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