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PLANETARY QUARANTINE

3 A MODEL FOR PLANETARY QUARANTINE REQUIREMENTS 6

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A Model for Planetary Quarantine Requirements

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September 1966

ABSTRACT

In this report, a model is developed which relates general planetary exploration objectives to spacecraft-oriented planetary quarantine requirements (sterility levels). This model is somewhat more realistic than previous models in that it considers only a finite number of missions.

When only finitely many missions are envisioned, the probability that a mission contaminates the planet is highly dependent upon the probability of mission success. So much so, in fact, that for certain (not unreasonable) parameter values, it is impossible to obtain a sterility level. In many other cases, even when a level can be obtained, it is impracticably severe. This suggests that further investigation will be needed before agreement is reached about spacecraft sterility levels.

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I. Apologia

Modeling is a dynamic activity, since a model is a function of one's ability to observe, and as this ability increases, changes may be required in the model. Furthermore, analysis of existing models may lead to contradictions, making a different model desirable. Thus, in arriving at a "satisfactory" model, it may be necessary to formulate "intermediate" models.

The first model in the area of planetary quarantine requirements was developed by C. Sagan and S. Coleman, and all of the subsequent models known to the authors have been based upon this original work. The Sagan-Coleman model generated planetary quarantine requirements under the assumption that an infinite number of missions may be launched. These requirements were discussed by the Committee on Space Research in 1964, and have been the basis of international agreement.

In this paper, a model is developed in which a finite upper bound on the number of missions that will be launched is assumed. Because of the nature of the conclusions that can be drawn from this model, it should be clearly understood that no claim is made that the model presented in this paper is the final "satisfactory" model desired by the planetary quarantine community. In fact, the authors view this model as an attempt to stimulate further thought about the tradeoffs between experimental success and planetary contamination.

It should also be pointed out that the numbers used in this report are for illustrative purposes and not necessarily those numbers which will ultimately be used in the exploration program. They have been chosen primarily because they correspond to numbers appearing in other modeling efforts, and this allows some comparison of results.

II. Introduction

At present, the Committee on Space Research (COSPAR) is looking forward to a period -- (1969-2021) -- of unmanned Martian exploration by the U.S.A. and the U.S.S.R. This unmanned phase of the planetary exploration program will make use of flyby, orbiter, and lander missions. A Martian flyby mission consists of a bus vehicle and space capsule that are intended to pass within a prescribed distance from Mars and then proceed into orbit about the sun. In the cases of the orbiter and lander missions, the respective bus vehicle and space capsule are injected together into a Martian orbit. Once in this orbit, the lander capsule is separated from its bus vehicle (which continues to orbit Mars), and is landed on the Martian surface.

This program of Martian exploration would be considered successful if

1) A series of scientific experiments were successfully completed,
2) Mars were not contaminated, and
3) these first two objectives were attained within the time and cost constraints of the program.

The words "successful program" and "contamination" are terms that require further delineation. "Successful program" refers to the attainment of all three program aims. Of course, the aim of non-contamination is the most critical aim because the contamination of Mars at an early stage of exploration would cancel any further possibility of unbiased exploration, and the contamination of Mars at a late stage of exploration would deny to future times and improved techniques the chance to work in an exobiological preserve. By contamination of the planet Mars is meant that at least one non-Martian viable microorganism has been introduced to Mars, found the necessary nutrients, and multiplied sufficiently to bias future exploration of the planet. At this stage of planning, with little known about the

Martian condition for supporting life, a conservative definition must be assumed. With more knowledge of Martian ecology this notion may be modified.

This burden of not contaminating Mars has to be recognized as a constraint and every effort is being made to work within its limits. To some, such a constraint is most easily observed by delaying or canceling the program, while others prefer to gain knowledge while minimizing the danger of contamination. It is at this crossroad that one attempts to pinpoint critical parameters in the program in order to maximize the chances of success while minimizing the risk of contamination.

A model relating the objectives of the unmanned Martian exploration program to hardware oriented subobjectives is developed and discussed in this report. Superficially, this model resembles other models developed for this same purpose, however, the model developed here more nearly represents "reality", and leads to somewhat different conclusions.

Because of the natural uncertainty about most of the parameters appearing in the model derived here, the model has been analyzed using many combinations of values for these parameters. This resulted in a large collection of data, most of which will appear in a forthcoming companion document.

Definitions of all of the pertinent model parameters are given in Section III. This is done primarily for introduction and reference purposes since these definitions are reiterated periodically throughout the report. In Section IV the model is developed and certain aspects of the numerical analysis needed for calculations are discussed. Section V is devoted to a discussion of the model primarily with regard to its significant features and its differences from previous models. Some sample calculations are used as illustrations. A complete sample calculation is presented in

Section VI. This is done to illustrate the way in which the model is to be used.

III. Formal Definitions

The first series of definitions in this section is given in order that there be at least a verbal preciseness about the overall program objective used in formulating the model. The program objectives are stated here in terms of successful missions, and this in turn is related to successful experiments. Reasons for this approach are discussed in the next section.

The Martian Exploration Program is a plan to scientifically investigate the planet Mars by unmanned lander, flyby, and orbiter missions.

The Martian Exploration Program would be considered successful, if

1. a) N_L lander missions are "successful",
   b) N_F flyby missions are "successful",
   c) N_O orbiter missions are "successful",
2. The planet Mars was not contaminated, and
3. (1) and (2) were attained within the time and cost constraints of the program.

A capsule's mission is termed successful, if Z% of its on board experiments are deemed to have worked.

An on board experiment will be said to have worked if telemetry data indicates that an on board experiment has functioned as planned.

The planet will be contaminated if, at any time prior to the last mission (determined by time constraints) there are present on the planet sufficiently many viable non-Martian microorganisms to bias future experimentation.

The objective of the Martian Exploration Program is that it be "successful" with probability greater than or equal to some number $\hat{P}$, $0 \leq \hat{P} \leq 1$.

The following definitions have been gathered here in order to provide a reference list of the more important terms for the reader. In most cases, these definitions have been re-stated when they are used, and in some cases a great deal of explicative motivation enters into a term which is found where the term is introduced in the model.

P = The probability of successfully completing a Martian Exploration Program.

P_L = The probability that a single lander capsule <u>contaminates</u> Mars.

P_F = The probability that a single flyby capsule <u>contaminates</u> Mars.

P_O = The probability that a single orbiter capsule <u>contaminates</u> Mars.

P_V = The probability that a single bus vehicle <u>contaminates</u> Mars.

E_L = Total number of experiments intended to be performed by the lander missions.

E_F = Total number of experiments intended to be performed by the flyby missions.

E_O = Total number of experiments intended to be performed by the orbiter missions.

N_L = The minimum number of successful lander missions needed to perform at least E_L experiments.

N_F = The minimum number of successful flyby missions needed to perform at least E_F experiments.

N_O = The minimum number of successful orbiter missions needed to perform at least E_O experiments.

$X_{L,i}$ = The number of experiments on board the i^{th} lander mission.

$X_{F,i}$ = The number of experiments on board the i^{th} flyby mission.

$X_{O,i}$ = The number of experiments on board the i^{th} orbiter mission.

$P_{L,S}$ = The probability of a successful lander mission.

$P_{F,S}$ = The probability of a successful flyby mission.

$P_{O,S}$ = The probability of a successful orbiter mission.

$P(k)$ = The probability that there are exactly k viable non-Martian microorganisms on board a lander capsule when it impacts on Mars.

ρ = The probability that there is <u>at least</u> one viable non-Martian microorganism on board the lander capsule when it impacts Mars.

= $1 - P(0)$, (where $P(0)$ is $P(k)$ with $k = 0$).

K_L, K_F, K_O, K_V are defined by equations (3) and (4).

$P_R(\tau|k)$ = The probability that exactly τ viable non-Martian microorganisms are released upon the Martian surface given that there are exactly k on board the lander capsule.

$P_B(\tau)$ = The probability that, given the release of τ viable non-Martian microorganisms on the Martian surface, future scientific exploration on the planet Mars is biased.

$P_D(k)$ = The probability that, given exactly k viable non-Martian microorganisms on board the lander capsule, at least one will be released onto the Martian surface, and bias future scientific exploration of the planet.

IV. The Model

The requirement that a Martian Exploration Program be successfully completed with probability P can be expressed by the equation (where, initially, for the sake of simplicity, the success of each mission is taken for granted):

$$P = (1-P_L)^{N_L} (1-P_F)^{N_F} (1-P_O)^{N_O} (1-P_V)^{N_L}, \text{ where} \qquad (1)$$

P = Probability of successfully completing the Martian Exploration Program with the risk of contaminating Mars of $(1-P)$,

$(1-P_L)$ = Probability that a lander capsule does not contaminate Mars,

N_L = Minimum number of lander missions needed to successfully complete the Lander phase of experimentation,

$(1-P_F)$ = Probability that a flyby capsule does not contaminate Mars,

N_F = Minimum number of flyby missions needed to successfully complete the Flyby phase of experimentation,

$(1-P_O)$ = Probability that an orbiter capsule does not contaminate Mars,

N_O = Minimum number of orbiter missions needed to successfully complete the Orbiter phase of experimentation, and

$(1-P_V)$ = Probability that a bus vehicle from a lander mission does not contaminate Mars.

Taking the natural logarithm of both sides,equation (1) becomes

$$\ell n\ P = N_L\ \ell n(1-P_L) + N_F\ \ell n(1-P_F) + N_O\ \ell n(1-P_O) + N_L\ \ell n(1-P_V). \qquad (2)$$

Equation (2) can be further broken into its component parts as follows:

$$K_L \; \ell n P = N_L \; \ell n(1-P_L), \tag{3 L}$$

$$K_F \; \ell n P = N_F \; \ell n(1-P_F), \tag{3 F}$$

$$K_O \; \ell n P = N_O \; \ell n(1-P_O), \text{ and} \tag{3 O}$$

$$K_V \; \ell n P = N_L \; \ell n(1-P_V), \text{ where} \tag{3 V}$$

$$0 \leq K_L, K_V, K_F, K_O \leq 1, \text{ and } K_L + K_F + K_O + K_V = 1 \tag{4}$$

Equations (3) can then be expressed as:

$$P^{K_L} = (1-P_L)^{N_L}, \tag{5 L}$$

$$P^{K_F} = (1-P_F)^{N_F}, \tag{5 F}$$

$$P^{K_O} = (1-P_F)^{N_O}, \tag{5 O}$$

$$P^{K_V} = (1-P_V)^{N_L}. \tag{5 V}$$

Equations (5) are an attempt to apportion the requirements for a totally successful program to the component parts of the program. That is, for example, if the Lander phase comprises 48% of the threat of contaminating Mars, the Flyby phase comprises 24% of the threat, the Orbiter phase comprises 16% of the threat and the Bus Vehicles comprise 12% of the threat, then because of the linearity of equation (2) one can calculate the K's in a straightforward way. In this case, $K_L = .1$, $K_F = .2$, $K_O = .3$, and $K_V = .4$. Since actual percentages are not known, the values of K_L, K_F, K_O, K_V must be treated as parameters.

As noted in the verbal description of (1), N_L, N_F, N_O are each the minimum number of missions required to complete a particular phase of experimentation. Of course, N_L, N_F, and N_O are also parameters dependent on the notions of a <u>successful</u> <u>Martian</u> <u>Exploration</u> <u>Program</u> which is dependent on the notion of a <u>successful mission</u>. If only the Lander phase of a successful Martian Exploration Program is considered (for the sake of avoiding redundancy) one would find that N_L is the minimum number of missions needed to satisfy the following inequality:

$$E_L \leq \sum_{i=1}^{N_L} Z_{L,i}\, X_{L,i}, \text{ where} \tag{6}$$

E_L = total number of experiments intended to be performed in the Lander phase,

N_L = the minimum number of successful lander missions needed to perform E_L experiments,

$Z_{L,i}$ = the percentage of experiments on board the i^{th} lander that must work in order to have the mission considered successful,

$X_{L,i}$ = the number of experiments on board the i^{th} lander mission, and

$Z_{L,i} \cdot X_{L,i}$ assumes only integer values.

Thus, the number N_L depends on E_L, $Z_{L,i}$, $X_{L,i}$. In the actual calculations, N_L was treated simply as a parameter of the model and its relationship to E_L, $Z_{L,i}$, and $X_{L,i}$ was neglected.

The decision to simplify N_L in this manner was made for practical reasons. At this stage E_L, $Z_{L,i}$, and $X_{L,i}$ are themselves still parameters which will be influenced by time and technique. If, however, one treats the number of lander missions as a parameter, one can neglect the undetermined values of E_L, $Z_{L,i}$, and $X_{L,i}$, and still obtain valuable information. Thus, values have been chosen for N_L, and no concern has been given to its precise relation to E_L, $X_{L,i}$, and $Z_{L,i}$ other than that it does satisfy inequality (6). (The same approach holds for N_F, and N_O.)

Even though numbers are chosen for N_L, N_F, and N_O, and a certain independence of on board experiments has been achieved, no account, up to this point, has been taken of the possibility of a mission failing. Since the success of a Martian Exploration Program has been determined in terms of successful missions, M_L extra lander missions, M_F extra flyby missions, and M_O extra orbiter missions may have to be flown to successfully complete at least E_L, E_F, and E_O experiments, respectively. Time and cost objectives (Section III) are two factors which limit the choice of values of M_L, M_F, M_O. Clearly also, the choice of N_L, N_F, N_O and the probabilities of success of lander, flyby and orbiter missions influence the choice of the number of additional flights to allow for failures. Thus, equation (1) must be modified to take into account these extra parameters.

One way of improving equation (1) to handle the probability of a mission failure (such as, non-soft impact that destroys on board equipment; on board experiment malfunction; telemetry malfunction; etc.) is to think in terms of a truncated negative binomial distribution [1,2].

Consider the following situation for the Lander phase of the Martian Exploration Program:

1. (N_L-1) lander missions have been successfully completed without contaminating Mars.
2. J_L lander missions have failed without contaminating Mars.
3. The $(N_L+J_L)^{th}$ lander mission will be successful, and not contaminate Mars.

Let

$\binom{N_L-1+J_L}{J_L}$ = the number of ways J_L failures can occur in N_L-1+J_L Lander missions,

$P_{L,S}$ = the probability of a successful lander mission,

$(1-P_{L,S})$ = the probability of an unsuccessful lander mission,

$(1-P_L)$ = the probability that a lander mission does not contaminate Mars,

N_L = total number of successful lander missions, and

M_L = total number of unsuccessful lander missions,

then P^{K_L} of equation (5 L) becomes the probability that we successfully complete N_L lander missions in N_L+M_L lander missions without contaminating Mars. Thus, equation (5 L) becomes:

$$P^{K_L} = \sum_{J_L=0}^{M_L} (1-P_L)^{N_L+J_L} \binom{N_L+J_L-1}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \tag{7 L}$$

Again, for emphasis, P^{K_L} is a <u>joint</u> probability of mission success <u>and</u> no contamination,using a finite number, (N_L+M_L),of missions. This is only reasonable since, if one's concern is only about contamination and not about a successful program, the best means of avoiding contamination is to fly no missions, while flying an infinite number of missions to guarantee a successful scientific program is clearly unrealistic.

If one defines

$P_{F,S}$ = the probability of a successful flyby mission, and

$P_{O,S}$ = the probability of a successful orbiter mission,

then equations (5 F), (5 O), and (5 V) become

$$P^{K_F} = \sum_{J_F=0}^{M_F} (1-P_F)^{N_F+J_F} \binom{N_F-1+J_F}{J_F} (P_{F,S})^{N_F} (1-P_{F,S})^{J_F}, \tag{7 F}$$

$$P^{K_O} = \sum_{J_O=0}^{M_O} (1-P_O)^{N_O+J_O} \binom{N_O-1+J_O}{J_O} (P_{O,S})^{N_O} (1-P_{O,S})^{J_O}, \tag{7 O}$$

and

$$P^{K_V} = (1-P_V)^{N_L+M_L}. \tag{7 V}$$

Multiplying equations (7 L), (7 F), (7 0) and (7 V), gives one the required generalization of equation (1), and the expression for successfully completing a Martian Exploration Program with lander, flyby, and orbiter missions without contaminating the planet Mars, that is:

$$\begin{aligned} P = & \sum_{J_L=0}^{M_L} (1-P_L)^{N_L+J_L} \binom{N_L-1+J_L}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \cdot \\ & \cdot \sum_{J_F=0}^{M_F} (1-P_F)^{N_F+J_F} \binom{N_F-1+J_F}{J_F} (P_{F,S})^{N_F} (1-P_{F,S})^{J_F} \cdot \\ & \cdot \sum_{J_O=0}^{M_O} (1-P_O)^{N_O+J_O} \binom{N_O-1+J_O}{J_O} (P_{O,S})^{N_O} (1-P_{O,S})^{J_O} \cdot \\ & \cdot (1-P_V)^{N_L+M_L}. \end{aligned} \tag{8}$$

Returning now to equation (7 F), note that P, K_L, P_L, N_L, M_L, and $P_{L,S}$ are all parameters of the problem and that each must be the object of careful study. In this report, several representative values of the various parameters have been chosen and the associated values of P_L calculated. (A similar analysis yields values for P_F, and P_O, while values for P_V can be found in a straightforward manner.)

In particular, attention will now be turned to P_L, the probability that a given lander capsule contaminates Mars. P_L is a function of:

(1) $k \geq 0$, the number of viable non-Martian microorganisms present on the lander capsule,

(2) $P(k)$, the probability that there are exactly k viable non-Martian microorganisms present on the lander capsule as it impacts Mars,

(3) The position of these microorganisms (exterior or interior),

(4) $P_R(\tau|k)$, the probability that exactly τ viable non-Martian microorganisms, given exactly k on board, are released upon the Martian surface, and

(5) $P_B(\tau)$, the probability that, given the release of τ viable non-Martian microorganisms on the Martian surface, future scientific exploration of the planet is biased.

Thus, P_L can be expressed by the following equation.

$$P_L = \sum_{k=1}^{\infty} \left\{ \sum_{\tau=1}^{k} P_R(\tau|k)\ P_B(\tau) \right\} P(k). \qquad (9)$$

The probability that there are exactly k viable non-Martian microorganisms present on the lander capsule as it impacts Mars, $P(k)$, depends upon:

(1) the final sterilization cycle, and

(2) the probability of picking up viable non-Martian microorganisms after sterilization and prior to impact on Mars (e.g., from the "dirty" exterior of the biological shield when it is separated from the lander capsule).

In all work so far this latter probability of introducing viable contamination to the lander capsule has been neglected. It has not been specifically introduced into this model, not because of its unimportance, but rather because of the additional study needed to handle it. Thus, in the model presented here, $P(k)$ abstractly represents both (1) and (2). In previous models $P(k)$ is only the probability that exactly k microorganisms survive a dry heat sterilization cycle, and depends on:

1. the type of microorganism, α,
2. the initial population present, n_o,
3. the length of exposure time, t, and
4. the sterilization temperature T.

The probability that a microorganism of type α survives a dry heat sterilization cycle of time duration t, at the given temperature T shall be denoted by $p(\alpha,t,T)$. Assuming that microorganisms die independently of one another leads to the usual binomial distribution for $P(k)$, the probability that exactly k microorganisms out of an initial population of n_o type α microorganisms survive a dry heat sterilization cycle of time length t at temperature T, given by:

$$P(k) = \binom{n_o}{k} [p(\alpha,t,T)]^k \, [1-p(\alpha,t,T)]^{n_o-k} . \tag{10}$$

In this study no assumption will be made as to what model best represents $p(\alpha,t,T)$. For a discussion of some of the models that could represent $p(\alpha,t,T)$, the reader is referred to [3].

The conditional probability, $P_R(\tau|k)$, that exactly τ viable non-Martian microorganisms are released on the Martian surface, given exactly k on board the lander capsule, is a function of the location of the microorganisms (that, is, interior or exterior) on the lander capsule. Further, define

$P_E(k_1|k)$ to be the probability of k_1 viable non-Martian microorganisms on the exterior of the lander capsule, given a total of k on the lander,

$P_I(k_2|k)$ to be the probability of k_2 viable non-Martian microorganisms in the interior of the lander capsule, given a total of k on the lander,

$\tilde{P}_R(E|\tau_1|k_1)$ to be the probability of release of τ_1 viable non-Martian microorganisms from the exterior given that there are k_1 on the exterior of the lander capsule,

$\tilde{P}_R(I|\tau_2|k_2)$ to be the probability of release of τ_2 viable non-Martian microorganisms from the interior given that there are k_2 on the interior of the lander capsule,

$P_R(E|\tau_1|k)$ to be the probability of release of τ_1 viable non-Martian microorganisms from the exterior of the lander capsule given that there are a total of k on the lander,

$P_R(I|\tau_2|k)$ to be the probability of release of τ_2 viable non-Martian microorganisms from the interior of the lander capsule given that there are a total of k on the lander, and

$P(\tau_1,\tau_2|k)$ to be the probability of release of τ_1 exterior and τ_2 interior viable non-Martian microorganisms given that there are a total of k on the lander.

Then

$P_R(\tau|k)$ can be represented by the following equation:

$$P_R(\tau|k) = \sum_{\tau_1+\tau_2=\tau} P_R(\tau_1,\tau_2|k), \text{ where} \tag{11}$$

$$P_R(\tau_1,\tau_2|k) = P_R(E|\tau_1|k) \cdot P_R(I|\tau_2|k), \text{ and} \tag{11a}$$

where, in turn,

$$P_R(E|\tau_1|k) = \sum_{k_1=\tau_1}^{k} \tilde{P}_R(E|\tau_1|k_1)\ P_E(k_1|k), \text{ and} \qquad (11b)$$

$$P_R(I|\tau_2|k) = \sum_{k_2=\tau_2}^{k} \tilde{P}_R(I|\tau_2|k_2)\ P_I(k_2|k). \qquad (11c)$$

Little is known of the values of $\tilde{P}_R(E|\tau_1|k_1)$ and $\tilde{P}_R(I|\tau_2|k_2)$. It is hoped, however, that a paper of the authors [6], will lead to ways of handling these parameters and $P_E(k_1|k)$, and $P_I(k_2|k)$.

Equation (9) will now be examined in more detail. Consider

$$P_L = \sum_{k=1}^{\infty} \left\{ \sum_{\tau=1}^{k} P_R(\tau|k)\ P_B(\tau) \right\} P(k), \qquad (12)$$

and, set

$$P_D(k) = \sum_{\tau=1}^{k} P_R(\tau|k)\ P_B(\tau). \qquad (12a)$$

Since there is not enough available data to exactly determine $P_D(k)$, (the probability that Mars is contaminated given that there are exactly k micro-organisms on board a lander capsule), it seemed appropriate to treat it as a parameter of the model. In particular, $P_D(k)$ is set equal to P_D for all k. This, of course, is an assumption, but one that does not distort reality too much, because $P_D(k)$ is a non-negative and bounded by 1 for all k. Thus, choosing $P_D(k) = 1$ for all k errs on the conservative side, and states that, if a viable non-Martian microorganism gets to Mars, it will contaminate the planet, while setting $P_D(k) = 0$ for all k states that no viable non-Martian microorganisms introduced to the Martian environment can possibly contaminate the planet. The true situation is most likely somewhere in the middle, and thus, $P_D(k)$ has been set equal to P_D, for all k.

Thus, with this assumption, equation (12) becomes:

$$P_L = P_D \sum_{k=1}^{\infty} P(k), \tag{12b}$$

and by summing equation (12b), we find

$$P_L = P_D(1-P(0)), \text{ or} \tag{12c}$$

$$P_L = P_D\ \rho, \tag{13 L}$$

Similar arguments can be made for P_F, and P_O and an equation similar to equation (12) can be developed. Skipping the details as repetitious,

$$P_F = P_{I,F} \sum_{k=1}^{\infty} P_D(k)\ \hat{P}(k), \text{ and} \tag{13 F}$$

$$P_O = P_{I,O} \sum_{k=0}^{\infty} P_D(k)\ \hat{P}(k), \text{ where} \tag{13 O}$$

$P_{I,\cdot}$ = is the probability that a flyby (orbiter) capsule impacts the planet, and

$\hat{P}(k)$ = P(k) of equation (10) with $p(\alpha,t,T)$ based on (perhaps) different values of t, and/or T.

For the lander phase, the parameters N_L, M_L, K_L and $P_{L,S}$ are given along with the inequality $P \geq \hat{P}$. Here $\hat{P}$ represents the least acceptable value for P, and has been given the value $\hat{P} = 0.999$ in all calculations. The probability 0.999 is the non-contamination criterion agreed to by the Committee on Space Research of the International Congress of Scientific Unions (v. [8], p.55). As such, it has been used by the authors of references [1], [4], [5], and others, as the primary objective of the planetary quarantine program. It is used in this document in a somewhat different sense, but because of the relationship between the model developed here and previous models (discussed in Section V), it was felt that the same number should be used for purposes of comparison.

Theoretically, then, the object is to solve the inequality

$$\hat{P}^{K_L} \leq P^{K_L} = \sum_{J_L=0}^{M_L} (1-P_L)^{N_L+J_L} \binom{N_L+J_L-1}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L}$$

for P_L, i.e., to obtain a number $\hat{P}_L$ such that for all $P_L \leq \hat{P}_L$, the inequality above obtains.

If, in fact, one solves

$$\hat{P}^{K_L} = \sum_{J_L=0}^{M_L} (1-P_L)^{N_L+J_L} \binom{N_L+J_L-1}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} ,$$

the solution, if it exists, will be $\hat{P}_L$. The object, then, is to solve this $(N_L+M_L)^{th}$ degree polynomial in P_L for $\hat{P}_L$. Because N_L+M_L is relatively large, this solution must be obtained numerically, and some attention must be paid to the accuracy of the solution.

Thus in the actual calculations, an upper bound, P_L(U.B.), and a lower bound, P_L(L.B.), for the maximum acceptable value of P_L are found. That is, the inequalities

$$P^{K_L} - \varepsilon \le \sum_{J_L=0}^{M_L} (1-P_L(U.B.))^{N_L+J_L} \binom{N_L-1+J_L}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \quad (14a)$$

$$\le P^{K_L}$$

$$= \sum_{J_L=0}^{M_L} (1-P_L)^{N_L+J_L} \binom{N_L-1+J_L}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \quad (14c)$$

$$\le \sum_{J_L=0}^{M_L} (1-P_L(L.B.))^{N_L+J_L} \binom{N_L-1+J_L}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \quad (14d)$$

$$\le P^{K_L} + \varepsilon \quad (14e)$$

are solved numerically for $P_L(U.B.)$ and $P_L(L.B.)$ when $P = \hat{P}$. This yields

$$P_L(L.B.) \le P_L \le P_L(U.B.), \text{ or} \quad (15)$$

$$P_L(L.B.) \le \rho P_D \le P_L(U.B.), \text{ or} \quad (16)$$

$$\frac{P_L(L.B.)}{P_D} \le \rho \le \frac{P(U.B.)}{P_D} \quad (17)$$

Calculations have proven that this gives a very good bound on the maximum acceptable value of ρ for small ε.

Similar arguments can be used to bound the maximum acceptable values of P_F and P_O, and, in particular,

$$P_F(L.B.) \leq P_F \leq P_F(U.B.), \text{ and} \tag{18}$$

$$P_O(L.B.) \leq P_O \leq P_O(U.B.) \tag{19}$$

On the other hand, the maximum acceptable value of P_V, is given by:

$$P_V = 1-P^{\frac{K_V}{D}}, \text{ where}$$

$$D = N_L+M_L, \text{ and } P = \hat{P}. \tag{20}$$

V. Analysis of the Model

The mathematical model developed in Section IV has introduced new notation for concepts that are used in recent articles of Sagan-Coleman [1], Schalkowsky [4], and Cornell [5]. This change of notation has been introduced to emphasize the need to formulate a model that conforms to the reality of the Martian Exploration Program, and to accurately define these fundamental concepts. In these recent articles Schalkowsky [4] and Cornell [5] with minor changes in notation and emphasis have based their work on the following approximation (10) of Sagan-Coleman [1]:

$$\ell n\ p^{-1} \approx \frac{\sigma\ P_m N}{P_e P_+ X} + nP_i. \tag{21}$$

Before treating the major conceptual difficulty that distorts each model from the reality it intends, attention will be focussed on showing why new notation was desired to accurately define the concepts involved in approximation (21).

In Section IV, the concept of a lander capsule contaminating Mars is introduced as a probability, P_L. As a concept, it corresponds to the same probability, P_-, of Sagan-Coleman and Cornell. The notational change is made primarily to emphasize that P_L relates to the lander phase of the exploration program. Further, Equation (12) of Section IV analyzes P_L more thoroughly than has been done previously.

There appears to be much confusion about the definition of σ appearing in approximation (21). In the Sagan-Coleman paper [1] it is called both "the mean number of organisms deposited" on the planet and "the probability that a single viable microorganism be deposited" on the planet's surface.

Cornell [5] calls σ "the mean number of organisms per capsule" but goes on to say that σ may be defined to be "the probability that a spacecraft landing on Mars will be contaminated" by using the relation $P_- = \sigma P_m$. However, $P_L = \sigma P_m$ is an incorrect mathematical relation when σ is treated as such a probability since P_L is a plural concept while P_m, the "probability that a given microorganism landed on the surface of Mars will be able to multiply and contaminate a sizeable fraction of the planet," is a singular concept.

If σ is treated as "the expected number of organisms on the spacecraft upon impact with the planet in question," then the approximation relating P_-, σ and P_m can be derived correctly as follows. Referring to (12) and (12a), the derivation is

$$P_L = P_- = \sum_{k=1}^{\infty} P_D(k)\ P(k) \tag{22a}$$

where

$$\sigma = \sum_{k=1}^{\infty} kP(k) \tag{22b}$$

and, ignoring the subtlety of release probabilities as given in Section IV,

$$P_D(k) = 1-(1-P_m)^k. \tag{22c}$$

Hence,

$$P_L = \sum_{k=1}^{\infty} P(k) - \sum_{k=1}^{\infty} (1-P_m)^k P(k) \tag{22d}$$

$$\doteq \sum_{k=1}^{\infty} P(k) - \sum_{k=1}^{\infty} [1-kP_m] P(k), \text{ when } P_m \text{ is small,} \tag{22e}$$

$$= P_m \sum_{k=1}^{\infty} kP(k) \tag{22f}$$

$$= \sigma P_m. \tag{22g}$$

If no serious account is taken of release probabilities then, $P_L \doteq \sigma P_m$ when P_m is small. Here, σ is quite clearly an expected number. When release probabilities are considered, the derivation given by equation (12) of Section IV is a correct one.

Schalkowsky [4], too, confuses mean number with probability in his summary of the Sagan-Coleman Analysis. He first defines σ (v. equation 21) to be the "probability of one viable microorganism on the surface of Mars due to a single lander." He then defines [4; equation (2)]:

$$\sigma = P_N \cdot P_R, \text{ where} \tag{23a}$$

P_N - probability of one viable microorganism aboard the lander, and

P_R - mean probability, that one microorganism, if present, will be released from the lander and deposited on the Martian surface.

In this way, Schalkowsky has introduced a sterilization criterion, P_N, as a "probability of one viable microorganism aboard the lander." In his equation (6), however, he sets

$$P_N = N_o \cdot 10^{-t/D}, \tag{23b}$$

and defines,

N_o - as the initial population of microorganisms on the lander (prior to the application of dry-heat),

t - as the length of time dry heat is applied at a particular fixed temperature, and

D - as the time it takes to reduce a single-species population by a factor of 10 at a fixed temperature.

Although the P_N of equation (23) is called a "probability", it is an expected number. Thus, σ and P_N are expected numbers of microorganisms, and not "the probability of a single viable microorganism aboard a lander." In a later paper [7], Schalkowsky recognized this difficulty and showed that, numerically, P_N is a good approximation to the "probability of a single viable microorganism aboard a lander" when $P_N \ll 1$.

Thus, in this paper

$$P_L = \rho\ P_D \tag{24a}$$

effectively replaces

$$P_{-} \cong \sigma\ P_m, \tag{24b}$$

for the following reasons:

1) ρ as a probability gives more information than σ, an expected number,

2) the derivation of P_D (v.(12)) is a more realistic approach to the problem of the release of interior and exterior contamination, and

3) the confusion surrounding the definition of σ is eliminated.

The probability, $P_{L,S}$, that a lander mission is successful, should not be confused with P_+ ([1], [4], [5]). In the initial development of the Sagan-Coleman model [1], when the expressions were derived for one experiment per mission, P_+ was taken to be "the mean probability that a landing capsule deposited somewhere on Mars will successfully perform its biological experiment." Later, when more than one experiment per mission was allowed, P_+ became "the probability of a successful landing," and no longer implied any experimental success. Referring to Section III, a successful mission, as defined in this paper, involves the success of some percentage, Z, of experiments,whence the probability, $P_{L,S}$, of a successful mission must also. This percentage may vary from mission to mission, allowing some flexibility in the notion of mission success. Also, this emphasis on a successful mission introduces the necessity of formulating the flyby and orbiter phases of the Martian Exploration Program separately as in equations (7 F) and (7 0) rather than as the last sum of approximation (21). The advantage of this formulation is that it provides a means of relating program success to experimental success rigorously by first relating each to mission success.

Finally, the major conceptual difficulty in the Sagan-Coleman paper [1] (and carried over by Schalkowsky [4] and Cornell [5]) is to consider $j(J_L = j$ in the notation of section IV), the number of missions that fail, to run from 0 to ∞ [v. equation (1):1]:

$$p = \sum_{j=o}^{\infty} \binom{N+j-1}{j} P_+^N (1-P_+)^j \; (1-P_-)^{N+j} \tag{25}$$

or in the notation of equation (7L):

$$P = \sum_{J_L=0}^{\infty} \binom{N_L+J_L-1}{J_L} P_{L,S}^{\ N_L} (1-P_{L,S})^{J_L} (1-P_L)^{N_L+J_L}. \tag{26}$$

Summing J_L from 0 to ∞ allows one to solve for P in closed form,

$$P = \left[\frac{P_{L,S}(1-P_L)}{1-(1-P_{L,S})(1-P_L)}\right]^{N_L}, \tag{27}$$

but is a distortion from the reality of the Martian Exploration Program, since equations (26) and (27) demand that we continue to send unmanned lander capsules to Mars until we have N_L successful missions (apparently without regard for the limitations of time or finances). To send an unlimited number of missions to Mars is an unrealistic concept, and not the intention of the space program. Rather, the Martian Exploration Program is formulated in terms of the following finite aims and constraints:

1. to successfully complete $N(N = N_L+N_F+N_O)$ missions,
2. to keep the risk of contamination of Mars small, and
3. to accomplish (1) and (2) by attempting no more than N' $(N' = N_L+M_L+N_F+M_F+N_O+M_O)$ space missions.

When N_L, M_L, P, K_L, and $P_{L,S}$ (in the case of the lander phase of the Program) are specified, one attempts to solve equation (7 L) for P_L. Since M_L is a fixed finite number, two very interesting difficulties come to light. The first difficulty is that for certain values of the parameters (for example, $N_L = 40$, $M_L = 10$, $P = 0.999$, $K_L = 0.5$, $P_{L,S} = 0.85$) no acceptable (between 0 and 1) value of P_L can be found that satisfies equations (7 L). Note, this is not the case if the closed form of Sagan-Coleman equation (27) is used, since, solving equation (27) yields

$$P_L = \frac{P_{L,S}[1-P^{(1/N_L)}]}{P_{L,S}[1-P^{(1/N_L)}]+P^{(1/N_L)}}$$

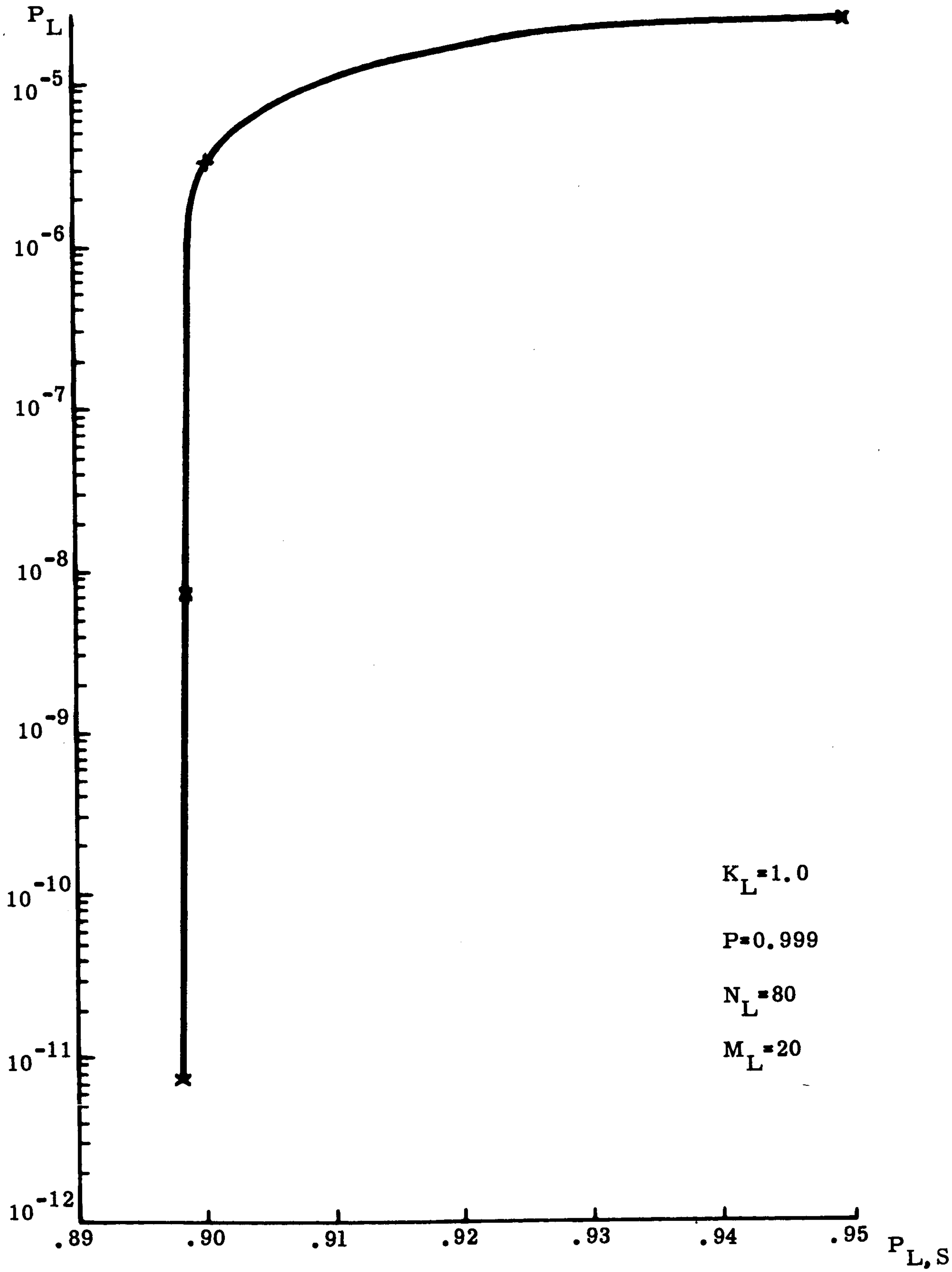
in which both numerator and denominator are nonnegative and the denominator is always greater than or equal to the numerator. That is, regardless of the numerical value of $P_{L,S}$, $0 \leq P_{L,S} \leq 1$, P_L is a number between zero and one. The second difficulty is the sensitivity of $P_{L,S}$ in equations (14). For example, if N_L, M_L, P, K_L are fixed, (say, $N_L = 80$, $M_L = 20$, $P = 0.999$, and $K_L = 1$), then P_L can be made as small as we want by varying $P_{L,S}$ as can be seen in the following table of values.

$P_{L,S}$	P_L
0.95	1.18×10^{-5}
0.90	2.17×10^{-6}
0.89832	6.39×10^{-9}
0.8983185	7.49×10^{-12}

TABLE 1

In this example, the dependence of P_L on $P_{L,S}$ can be seen to be extremely sensitive around $P_{L,S} = 0.90$. At this point, a slight change in $P_{L,S}$ downward yields a great change in P_L in the same direction. Since $P_L = \rho P_D$, this causes an equally great change in ρ, necessitating extreme sterilization efforts which would likely be unacceptable to the engineering community. Again, it must be noted, that the sensitivity of $P_{L,S}$ can not be detected if one uses the closed form of equation (27).

Figure 1 is a visual display of TABLE 1, and vividly illustrates the two difficulties inherent in the necessity of choosing M_L, finite. That



P_L
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
.89
.90
.91
.92
.93
.94
.95
$P_{L,S}$
$K_L=1.0$
$P=0.999$
$N_L=80$
$M_L=20$

FIGURE 1

is, given any values of the parameters (in this example, $P = .999$, $K_L = 1.0$, $N_L = 80$, and $M_L = 20$) there exist values of $P_{L,S}$ such that there is no acceptable value for P_L (in this example, it is for values of $P_{L,S} < .89$), and there exists a critical point for $P_{L,S}$ such that for values of $P_{L,S}$ just slightly less than it, P_L, goes to zero very rapidly (in this example it is for $P_{L,S}$ approximately equal to 0.90). Hence, it is entirely possible to have a sterilization criterion of $P_L \leq 10^{-50}$, or even worse.

In order to re-emphasize the point, it must be noted that whatever values of the parameters (K_L, P, N_L, and M_L) are given, there is a curve similar to that of Figure 1 associated with them. That is, given any values for K_L, P, N_L, and M_L, there are values for $P_{L,S}$ for which no acceptable solution for P_L exists, and there is a critical value for $P_{L,S}$ such that there is a value of $P_{L,S}$ slightly less than the critical value which gives values for P_L as <u>close as one wants to zero</u>!

These difficulties are rooted right in the mathematics of the model and the definition of P^{K_L} (a <u>joint</u> probability) as the probability of:

1) successfully completing at least E_L scientific experiments on Mars, and
2) not contaminating Mars.

Consider the following part of equation (26):

$$\binom{N_L+J_L-1}{J_L}(P_{L,S})^{N_L}\,(1-P_{L,S})^{J_L}, \tag{28}$$

which represents the probability of successfully completing at least E_L experiments by the $(N_L+J_L)^{th}$ lander mission. Since, P^{K_L} is a <u>joint</u> probability, the probability distribution, P_S, for successfully completing at least E_L scientific experiments in N_L+M_L missions (which is made up of a sum of terms from equation (28))

$$P_S = \sum_{J_L=0}^{M_L} \binom{N_L+J_L-1}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \tag{29}$$

must be greater than or equal to P^{K_L}. If it is less than P^{K_L}, there is no acceptable value for P_L, if it is equal to P^{K_L}, then $P_L = 0$ is the only solution, and if it is greater than P^{K_L}, there are acceptable solutions, and a critical point.

In summary, the development of a model for the Martian Exploration Program which is based on a finite maximum number of missions has the certain advantage of truly representing the reality of the Martian Exploration Program, and leads directly to the discovery of the sensitivity of $P_{L,S}$ in two important ways. First, the model proves (actual calculations will be discussed in Section VI) that if $P_{L,S}$ is too small, there may be no acceptable solution for P_L, and secondly, that if $P_{L,S}$ is given plus or minus an error term, the $P_{L,S}$ that is used in the calculations must be $P_{L,S}$ plus the error term (as can be seen in TABLE 1, and Figure 1) because $P_{L,S}$ may be near a critical value. That is, referring to TABLE 1, if $P_{L,S}$ is given as 0.90 ± 0.01, the sterilization criterion (on P_L) is <u>impossible</u> to determine in that range. If, however, $P_{L,S}$ is given as 0.90, + 0.01, - 0.00, then P_L is given as $P_L \leq 2.17 \times 10^{-6}$.

VI. A Numerical Example

In this section the various parameter values used in calculating values for P_L, P_F, P_O, and P_V will be set down, and the values of P_L, P_F, P_O and P_V associated with a particular Martin Exploration Program will be derived and stated for one particular set of parameter values. It will be the task of a companion paper to set forth the actual computer programs, and to collate and present the data.

Data has been generated to yield values of P_L, P_F, P_O, and P_V for all the combinations of the following parameters:

P = 0.999

K_L or K_F or K_O or K_V = 0.05 to 1.0 in steps of 0.05

N_L or N_F or N_O = 10 to 100 in steps of 10

$P_{L,S}$ or $P_{F,S}$ or $P_{O,S}$ = 0.50 to 0.95 in steps of 0.05

M_L and M_F and M_O were bounded by 100.

Further, values for P_S (v. equation (29)) were calculated for all the discrete combinations of the following parameters:

N_L or N_F or N_O = 10 to 120 in steps of 10,

$P_{L,S}$ or $P_{F,S}$ or $P_{O,S}$ = 0.50 to 0.95 in steps of 0.05, and

M_L or M_F or M_O = 0 to 100 in unit steps

As mentioned earlier, this data will be presented in a companion publication.

Attention will now be turned toward the following Martian Exploration Program:

1) P is set as 0.999,

2) A minimum of 70 lander missions are needed to successfully complete at least E_L scientific experiments on Mars, i.e., $N_L = 70$,

3) $P_{L,S}$ is given as 0.85,

4) these 70 lander missions constitute 48% of the risk of contaminating the planet,

5) a minimum of 30 flyby missions are needed to successfully complete at least E_F scientific experiments, i.e., $N_F = 30$,

6) $P_{F,S}$ is given as 0.90,

7) these 30 flyby missions constitute 24% of the risk of contaminating the planet,

8) a minimum of 20 orbiter missions are needed to successfully complete at least E_O scientific experiments, i.e., $N_O = 20$,

9) $P_{O,S}$ is given as 0.80,

10) these 20 orbiter missions constitute 16% of the risk of contaminating the planet,

11) there will be 70 bus vehicles and their debris that must avoid the planet,

12) these 70 vehicles and their debris constitute a risk of 12% of the risk of contaminating the planet.

With this data, the values of K_L, K_F, K_O, and K_V can be calculated in the usual way, while the acceptable values of M_L, M_F, M_O require a pre-knowledge of the probability distribution P_S and the value of $P_{L,S}$, $P_{F,S}$ and $P_{O,S}$, respectively. Presented schematically, the values of the parameters can be seen in TABLE 2.

The numbers used in this example are for illustrative purposes only, and are intended to show some of the difficulties that might be encountered in current approaches to the problem. They were chosen for use here because they are comparable with those occurring in other recent studies (v. [9], p.10).

Missions	Probability of Mission Success	Minimum Number of Extra Missions	% of risk	K
$N_L = 70$	$P_{L,S} = 0.85$	$M_L = 29$	48%	$K_L = 0.1$
$N_F = 30$	$P_{F,S} = 0.90$	$M_F = 12$	24%	$K_F = 0.2$
$N_O = 20$	$P_{O,S} = 0.80$	$M_O = 16$	16%	$K_O = 0.3$
$N_V = 99$			12%	$K_V = 0.4$

TABLE 2

Values were then computed for P_L (v. equations (14) with $\varepsilon = 10^{-9}$), P_F, P_O, and P_V. These results are presented in TABLES 3, 4, 5, 6. Since the upper and lower bounds agreed to at least four significant figures, only three significant figures are written in the Tables.

M_L	Maximum Acceptable values of $P_L = \rho P_D$
29	1.69×10^{-7}
30	7.18×10^{-7}
31	9.84×10^{-7}
32	1.11×10^{-6}
33	1.17×10^{-6}
34	1.19×10^{-6}

TABLE 3: $N_L = 70$, $P_{L,S} = 0.85$, $K_L = 0.1$

M_L	Maximum Acceptable values of P_F
12	1.36×10^{-6}
13	4.60×10^{-6}
14	5.60×10^{-6}
15	5.89×10^{-6}
16	5.97×10^{-6}
17	6.00×10^{-6}

TABLE 4: $N_F = 30$, $P_{F,S} = 0.90$, $K_F = 0.2$

M_O	Maximum Acceptable values of P_O
16	3.28×10^{-6}
17	8.48×10^{-6}
18	1.06×10^{-5}
19	1.14×10^{-5}
20	1.18×10^{-5}
21	1.19×10^{-5}

TABLE 5: $N_O = 20$, $P_{O,S} = 0.80$, $K_O = 0.30$

N_V	Maximum Acceptable values of P_V
99	4.04×10^{-6}
101	3.96×10^{-6}
102	3.92×10^{-6}
104	3.84×10^{-6}

TABLE 6: $K_V = 0.4$

If one recalls that $P_L = \rho P_D$ (v. equation 13), then values of ρ, the probability of one or more microorganisms on board a lander capsule as it impacts Mars, are calculated in TABLE 7 for various values of P_D.

M_L	$P_D = 1$	$P_D = .1$	$P_D = .01$	$P_D = .001$
29	1.69×10^{-7}	1.69×10^{-6}	1.69×10^{-5}	1.69×10^{-4}
30	7.18×10^{-7}	7.18×10^{-6}	7.18×10^{-5}	7.18×10^{-4}
31	9.89×10^{-7}	9.89×10^{-6}	9.89×10^{-5}	9.89×10^{-4}
32	1.11×10^{-6}	1.11×10^{-5}	1.11×10^{-4}	1.11×10^{-3}
33	1.17×10^{-6}	1.17×10^{-5}	1.17×10^{-4}	1.17×10^{-3}
34	1.19×10^{-6}	1.19×10^{-5}	1.19×10^{-4}	1.19×10^{-3}

TABLE 7: Maximum Acceptable Values of ρ.

TABLES 3, 4, 5 and 7 along with Figures 2 and 3 display the data for a particular example of a possible Martian Exploration Program, and reveal two noteworthy aspects of the mathematical model. The most interesting of these is that P_L, P_F, and P_O are increasing functions of the number of extra missions planned, which certainly contradicts intuition. That is, intuition suggests that the allowable risk per mission should decrease as the number of missions increases. The model, however, is formulated mathematically in terms of the joint probability of successfully performing at least E experiments and not contaminating Mars. Thus, precisely because P is a joint probability, as the probability of successfully performing at least E experiments grows greater, then the model allows the constraint on the probability of not contaminating the planet to grow smaller (within bounds), and vice versa.

In the actual application of this model to a given Martian Exploration Program, it seems best to set conservative values for P_L, P_S, and P_O. That is, to set the values for the P's at that value associated with the minimum number of extra missions needed to successfully complete at least the prescribed number of experiments (for each phase of the Program). This conservative value then covers all possibilities and gives an added margin of safety. In the Lander phase of this example, this would mean $P_L = 1.69 \times 10^{-7}$ (v. TABLE 3). This value would automatically cover the cases where:

1. exactly 29 extra Lander missions are needed and no more are to be flown, and
2. exactly 29 extra missions are needed and it has been decided to fly X more, and
   a. X more are actually flown, or
   b. less than X more are flown.

In the first case, the value for P_L is precise, while in the second case it may be conservative. Given Case 2a, it certainly would be conservative, but if Case 2b should occur for some reason it could prove to be very precise. Since one cannot rule out Case 2b, a conservative choice for P_L can not be ruled out. Needless to say, similar arguments can be made for P_F and P_O.

The second interesting aspect of the model is its critical dependence on the probability of successfully completing a mission. This dependence is clearly in evidence in the TABLES and Figures. If one contrasts TABLE 4 with TABLE 5, it is of particular interest to note that in TABLE 4 which treats the Flyby phase with a probability of mission success of .90, 12 extra missions are needed to successfully complete the 30 required missions, while in TABLE 5 with a mission probability of success of .80, at least 16 extra missions are needed to successfully complete only the 20 required missions.

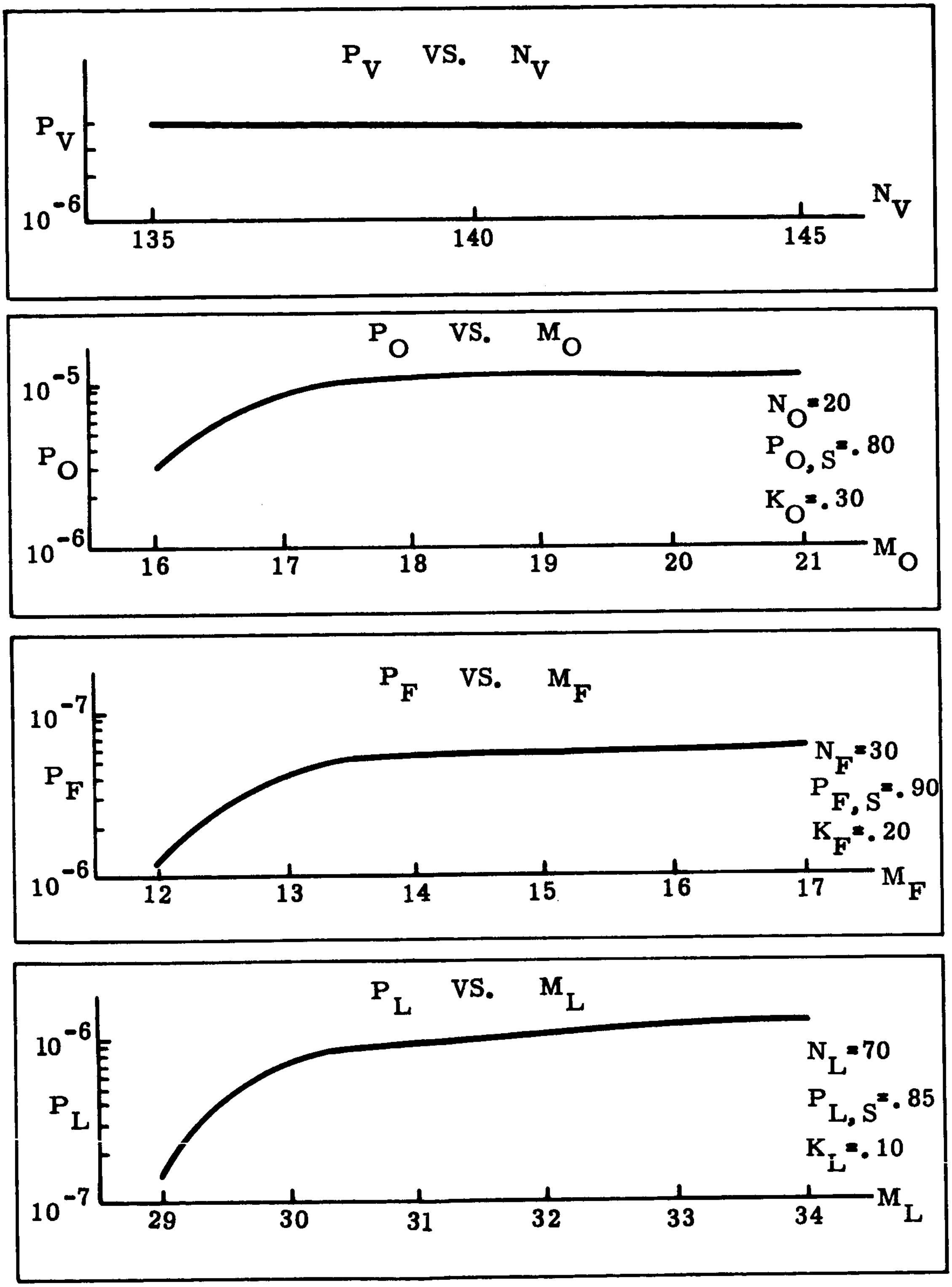


FIGURE 2: VISUAL DISPLAY OF TABLES 3, 4, 5, 6

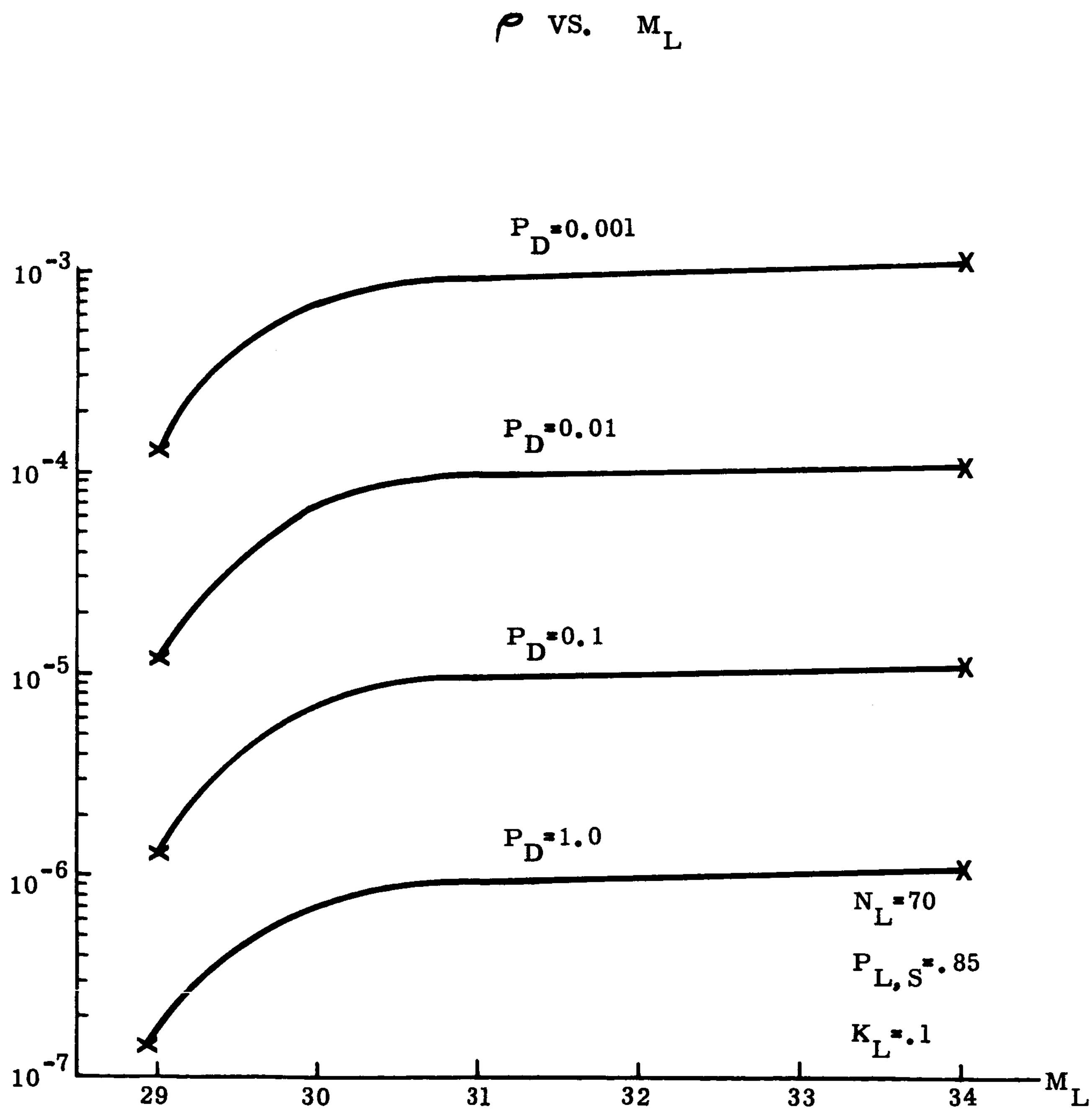


FIGURE 3: VISUAL DISPLAY OF TABLE 7

This, again, lucidly shows the critical dependence of the Martian Exploration Program on the probability of successfully completing each mission.

Finally, a word must be said in reference to TABLE 7 and Figure 3, which display ρ versus P_D. If one recalls that $\rho = 1-P(0)$ (where $P(0)$ is the probability of having no viable non-Martian microorganisms on board the lander capsule after the final dry heat sterilization cycle) and that $P(0)$ is the goal of the sterilization program, then P_D becomes a very important parameter. Figure 3 graphically shows the more that is known about P_D, the more the constraint on ρ and $P(0)$ can be relaxed.

In conclusion, it is hoped that this example of a possible Martian Exploration Program has helped to exemplify the importance of the various parameters. As promised in the beginning of this section, a companion report is in preparation which will present and further comment on the data generated in preparing this report.

VII. Summary

In this document, a model is developed which relates total planetary exploration program objectives to spacecraft oriented subobjectives. This is done by first decomposing the exploration program into three phases: the lander, orbiter and flyby phases. Each phase, in turn, is a series of missions, and each mission a collection of experiments. The notion of a successful experiment is defined, and this leads directly to the definitions of a successful mission, a successful phase and a successful exploration program. In particular, the exploration program is said to be successful if some required number of experiments is performed successfully by each phase of the program without contaminating the planet. Contamination, in this context, means the deposition of sufficiently many viable terrestial microorganisms on the planet to "bias further biological experimentation."

The model then assumes that the objective of the planetary exploration program is that the probability of its successful completion, P, should not be less than some prescribed lower bound. The lower bound is to be prescribed by a policy decision, and in current literature, as well as in this report, it is assumed to be 0.999.

Mathematically, each of the phases (lander, flyby and orbiter) is represented in the model by an expression of the form

$$P^K = \sum_{J=0}^{M} (1-P_C)^{N+J} \binom{N+J-1}{J} P_S^N (1-P_S)^J$$

where

P - is the probability of total exploration program success,

K - is a number, $0 \leq K \leq 1$, "proportioning" the success to the phase in question,

P_C - is the probability that a given mission in this phase biologically contaminates the planet (assumed constant),

P_S - is the probability that a given mission be successful (this refers to technological success independent of contamination),

N - is the minimum number of successful missions needed to successfully complete the given phase of the total exploration program, and

M - is the number of additional missions that one is willing or able to launch in order to increase the probability of success of this program phase.

The above expression represents the probability of completing N missions successfully in N + M total missions (in the phase in question) without biologically contaminating the planet. Accordingly, P^K is called the "probability of successfully completing" the phase in question. The model assumes that the objective of any given phase may be stated as "the probability of successfully completing the phase should not be less than some prescribed lower bound". With this objective, for each fixed set of parameters K, N, M, P_S, one may obtain a requirement on P_C.

The probability, P_C, of biological contamination from a single spacecraft, is related, in the model, to P(0), the probability of having no viable terrestial microorganisms aboard the spacecraft at the time of planetary impact. Thus, the requirement on P_C leads to a requirement on P(0), that is, the probability that the spacecraft is sterile must not be less than some lower bound. Thus, if P(0), the probability that the spacecraft is sterile is sufficiently near 1, then the probability of contamination per spacecraft, P_C, will be sufficiently low to guarantee that the probability of success of the phase in question will be large enough to insure that the program objective is achieved. Thus, the requirement that the probability of spacecraft sterility exceed some lower bound becomes a hardware oriented subobjective that must be achieved.

This analysis may be performed for any fixed set of parameters P,K,N,M and P_S. Because of the uncertainty surrounding many of these parameters, the model should be analyzed using many combinations of values for them.

One feature of the model is that, for fixed values of K,N & M, the value of P(0) is very sensitive to variations in P_S in some ranges of P_S. Thus, for example, if $N = 80$, $M = 20$, $P = 0.999$, $K = 1$ and $P_D = 1$, $1-P(0) \leq 2.17 \times 10^{-6}$ if $P_S = 0.90$ while $1-P(0) \leq 7.49 \times 10^{-12}$ for P_S slightly greater than 0.89. Thus one must take care to avoid ranges of P_S in which this is the case. A companion document in preparation will treat this sensitivity in more detail.

It is the objective of this document, and subsequent companion documents to:

- Present a model which may be used to relate planetary exploration program objectives to engineering subobjectives whose achievement will lead to the achievement of the planetary exploration program objectives,
- Point out possible pitfalls to be avoided in order that the program objectives be achieved (for example, the sensitivity of a choice for P_S, the probability of engineering mission success), and
- Present a tabulation of possible parameter values along with the consequences (that is,requirements on parameters such as P(0), the probability of spacecraft sterility) of choosing these values.

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