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ANALYSIS OF PLANETARY QUARANTINE REQUIREMENTS*

by

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Abstract

A simple but adequate analytical framework is provided to define the relationship between planetary quarantine requirements and estimated probabilities of planet contamination. Emphasis is placed on the form in which the requirements are to be stated so as not to constrain their implementation unnecessarily. Specific numerical values for the requirements are given, based on an assumed set of values for the "judgment factors" which enter into the analytical model. Alternate sets of requirements are compared and discussed.

A detailed definition of nomenclature is provided to encourage standardization of future analysis in this area.

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NOMENCLATURE

In the nomenclature defined below, the following symbol categories are used:

(a) Capital P will denote a probability of planetary contamination

(b) Lower case p will denote an event probability which is a component of a planetary contamination probability (P).

(c) Prime superscripts, e.g. P' or p', will denote probabilities relating to unsterilized organisms. The absence of a prime thus denotes probabilities relating to organisms which have undergone sterilization.

n_L - number of lander vehicles launched over the time-period under consideration. These landers will be sterilized in their entirety prior to launch.

n_U - number of unsterilized buses, orbiters and fly-bys launched over the time-period under consideration.

P - probability that any one landing vehicle, i.e. any one of the n_L's will contaminate the planet or its atmosphere.

P' - probability that any one of the unsterilized buses, orbiters, or fly-bys, i.e. any one of the n_U's will contaminate the planet or its atmosphere.

P_c - probability that the planet will be contaminated during the time-period under consideration.

p_P - probability that one viable organism in a lander previously subjected to heat sterilization, will be present on the planet surface or in its atmosphere.

p'_P - probability that one or more viable organisms not previously heat sterilized will be present on the planet surface or in its atmosphere.

p_G - probability that a viable, but previously heat sterilized, organism present on the planet surface will grow and spread so as to contaminate the planet or its atmosphere.

p'_G - probability that the one or more viable organisms which have not previously been heat sterilized and are present on the planet surface or in its atmosphere, will grow and spread and contaminate the planet or its atmosphere.

p_N - probability that one organism in a lander vehicle will remain viable after heat sterilization and transit to the planet.

p_R - probability that a viable organism if present in a sterilized lander will be released onto the planet surface.

N - number of viable organisms in a lander after heat sterilization.

No - number of viable organisms in a lander prior to heat sterilization.

t - heat sterilization time

D - time to reduce population of viable organisms by a factor of 10 at the selected sterilization temperature.

N'_o - number of viable organisms on an unsterilized spacecraft, or portions thereof, at the time it reaches a position to become a contamination hazard.

N' - number of viable organisms from an unsterilized spacecraft which are deposited on the planet surface or in its atmosphere.

p'_T - probability that one or more viable, but previously unsterilized organisms will be transferred from a bus, orbiter, or fly-by to the planet or its atmosphere.

p'_R - probability that viable, but previously unsterilized organisms transferred to the planet will be released onto the planet surface or into its atmosphere.

p'_N - probability of one viable organism not previously heat sterilized, on that planet surface or in its atmosphere.

Note: N and p_N refer to organisms on a lander prior to release (with probability p_R) onto the planet surface or its atmosphere. However, N' and p'_N refer to organisms after release (with probability p'_R) onto the planet surface or into its atmosphere.

ANALYTICAL FRAMEWORK

A simple analytical framework can be established on the basis of the following:

(1) planetary contamination probabilities due to any one vehicle will be much smaller than 1.

(2) the above probabilities will be taken to be constant for all the cases in any one category over the time-period under consideration.

Using the nomenclature previously defined, we can write:

$$P_c = n_L P + n_U P' \qquad (1)$$

We can further define P and P' as follows:

$$P = p_P \cdot p_G \qquad (2)$$

$$P' = \overset{i}{\Sigma} (p'_P \cdot p'_G)_i \qquad (3)$$

Equation 3 is written as a sum of i terms to allow for the various sources of planetary contamination involving unsterilized organisms, recognizing that different values of p'_P and / or p'_G may be associated with each case. The cases included in this category are (1) accidental impact of the entire unsterilized vehicle (2) contamination due to ejecta from the unsterilized vehicle (3) contamination due to emissions from the unsterilized vehicle (4) recontamination of a sterilized lander, and other sources of contamination which may come to light in future investigations.

It is to be noted that p_P and p'_P become mission design requirements for landers and unsterilized vehicles, once specific values of P_c, n_L, n_U, p_G and p'_G are accepted. These requirements are further defined to consist of the following component probabilities.

$$p_P = p_N \cdot p_R \qquad (4)$$

$$p'_P = p'_T \cdot p'_R \qquad (5)$$

Equations 4 and 5 are essentially operational equations, for use in implementing mission requirements. Each of the terms on the right hand side would be suitably expanded to represent the particular case being analyzed, e.g. p_N for heat cycle specifications, p'_T for contamination due to ejecta, etc.

Most, and probably all, analyses performed to date on planetary contamination probabilities and related mission requirements, can be reduced to the simple framework defined above without loss in the accuracy of predicting planetary contamination probabilities. This applies to the Sagan-

Coleman analysis which provided the basis for the evolution of earlier planetary quarantine requirements.

The complete equation for planetary contamination probability can be written as follows where each variable is identified by a brief title:

$$P_c = n_L \, p_N \, p_R \, p_G + n_U \sum^{i} (p'_T \, p'_R \, p'_G)_i \qquad (6)$$

probability of growth and spreading

probability of release on planet

probability of transfer to planet

number of unsterilized vehicles

probability of growth and spreading

probability of release from lander

probability of one organism in lander

number of landers

DEFINITION OF QUARANTINE REQUIREMENTS

Referring to equation 1, we adopt the following values for P_c, n_L and n_U as representing a desirable goal for the prevention of planetary contamination during unmanned exploration of Mars:

$$P_c < 10^{-3};\ n_L = 70;\ n_U = 30$$

The above choices define a probability of planetary contamination of less than 1/1,000 for 100 vehicle launches to Mars. The division of the total number of vehicles into 70 landers and 30 unsterilized buses, orbiter and fly-bys does not define a unique division of the total allowable contamination probability of $P_c < 10^{-3}$ between P and P'. Specific choices of P and P' are properly left as system trade-off parameters. However, the selection of n_L and n_U places an upper limit on P and P'. For, clearly, P or P' can not be chosen to be less than zero. Hence,

$$P' < 3.33 \times 10^{-5}$$

$$P < 1.43 \times 10^{-5}$$

It is also necessary to assign specific values to p_G and p'_G in order to remove these judgment factors from the domain of engineering implementation of quarantine requirement. We adopt a value of

$$p_G = 10^{-3}$$

as a suitable probability of growth and spreading due to one viable organism which, although viable, has previously been subjected to heat sterilization.

For the case of viable organisms from unsterilized vehicles, it should be noted that to accomodate the various possible sources of hazard, it was necessary to define p'_p as the probability of "one or more" organisms on the planet surface. It is therefore also necessary to relate p'_G to the number of viable, but unsterilized organisms ultimately released onto the planet surface (or its atmosphere) in any one of the i events being considered. We thus adopt the following values:

When $N' \geq 100$ $\quad p'_G = 1$

When $1 \leq N' < 100$ $\quad p'_G = N' \cdot 10^{-2}$

When $N' < 1$ $\quad p'_G = p'_N \cdot 10^{-2}$

The last of the above cases merely expresses the fact that when a calculation yields $N' < 1$, the value of N' is assumed equal to the probability of having one viable survivor. This is analagous to the procedure used in extrapolating survivor curves in heat sterilization to a probability of one survivor.

It is to be noted that when large numbers of viable organisms are anticipated, i.e. 100 or more, the probability of growth and spreading is taken to be unity. For small numbers, the comparison is most conveniently made for the case of one survivor. Thus, when $N' = 1$, we use a value of $p'_G = 10^{-2}$ which is one order of magnitude larger than p_G. This is intended to reflect the estimate that an organism not previously subjected to heat sterilization is more likely to grow in the Martian environment.

The choice of parameters made constrains the possible values of p_P and p'_P. With regard to the probabilities of release p_R and p'_R, it is to be expected that in most instances they would at first be taken to be unity. However, their evaluation is amenable to engineering analysis and may, in specific instances, be reliably demonstrated to be less than unity. These parameters are therefore considered to belong to the implementation process along with p_N and p'_T.

In terms of the values adopted above, planetary requirements would be given by the following:

(1) Planetary contamination probabilities (equation 1):

$$70P + 30P' \leqslant 10^{-3}$$

or

$$0.7\,P + 0.3\,P' \leqslant 10^{-5} \qquad (7)$$

(2) Sterilized landers (equation 2):

$$P = 10^{-3}\,p_P$$

or

$$p_P = 10^{3}P \qquad (8)$$

As previously noted, regardless of the allocation made between P and P', P cannot be greater than 1.43×10^{-5}. Hence, p_P will be less than 1.43×10^{-2}. The exact value will depend on the relative difficulty of achieving requirements for sterilized and unsterilized vehicles, effects of allocation choices on mission success probabilities and other mission design considerations.

(3) Unsterilized vehicles (equation 3):

In view of the need to provide for the different modes of contamination by unsterilized organisms, a simple statement for this requirement cannot be made. It must thus be defined in terms of equation 3 and the values of p'_G given herein. We note however, that P' will in any event be less than 3.33×10^{-5}, the exact value depending on the allocation between P and P' as discussed above.

To illustrate the application of requirements for unsterilized vehicles, consider the following specific cases:

(a) Accidental impact of the entire vehicle.

The probability of transfer p'_T is in this case the probability of accidental impact of the entire vehicle. Since the number of organisms on board is >>100 and the probability of release, p'_R, is unity (crash landing) p'_G would be taken as unity.

(b) Ejecta due to meteoroid impact.

p'_T would, in this case, denote the probability that ejecta from the spacecraft will reach the planet or its atmosphere. p'_R would represent the probability of releasing viable organisms from the ejecta. Before selecting p'_G it will be necessary to estimate how many of the organisms transferred are likely to be released onto the planet surface or its atmosphere. This will depend upon the number originally present and the physical mechanism of ejection from the vehicle, transfer to the planet and release of viable organisms from the ejecta.

(c) Emission in attitude control jets.

This case is analogous to ejecta except that the physical mechanisms are different. Thus, p'_T is again the probability that reaction-jet particles containing one or more viable orgainsms will be transferred to the planet. The probability of release of organisms from the particles may in general be close to unity. However, it may be found that only a small number of viable organisms can reach the planet surface or its atmosphere. Indeed, calculations may show that there is a probability of less than unity that one such organism will ultimately be deposited on the planet, even though the probability that some part of the attitude control jet gas will be transferred to the planet is near unity. A relatively smaller number for p'_G would be calculated in this case, as previously specified, so as to properly reflect the contribution of this source of hazard to the overall contamination probability.

DISCUSSION

A major difference between the requirements as described in the preceding section and current quarantine standards is in the format in which they are formulated. The relatively simple form used earlier, i.e. the definition of a required p_N and a single value of p'_T (referred to as the impact probability P_i), was appropriate to the early phases of the planetary quarantine program. Requirements as described herein are better suited to current needs in that -

(1) they do not unnecessarily constrain mission planning since the allocation of contamination probabilities between landers and unsterilized vehicles is, within specified bounds, left to trade-off studies appropriate to the agency called upon to implement the program;

(2) they take into account the various modes of contamination due to unsterilized vehicles and define constraints appropriate to those modes;

(3) parameters which are amenable to engineering analysis, i.e., p_R and p'_R are not eliminated from continuing evaluations by a priori specifications as part of the quarantine requirements.

In addition, the requirements described herein make use of updated numerical values of n_L, and p_G to reflect current consensus on these judgment factors.

To make a more detailed comparison, it would be necessary to reduce the general requirements described herein to a specific case which would be analogous to earlier considerations. To do this, we assume that the only possible mode of contamination from unsterilized vehicles is that of accidental impact by the entire vehicle. Table I shows resulting values of the various parameters for two cases using the present model. Case (a) (item 4 of Table I) assumes the same distributions between P and P' as was used in items 1, 2 and 3. Case (b) (item 5) shows a distribution which favors unsterilized vehicles by a factor of 31. Data for the Sagan and Coleman analysis (item 1) have been taken from the article published in the May 1965 issue of Aeronautics and Astronautics (p. 22). Item (2) of Table I represents a correction in the Sagan and Coleman data stemming from a minor error in their numerical calculations. As regards the COSPAR values, only p_N and p'_T are formally provided in COSPAR resolutions. The other values in item 3 are therefore inferred on the assumption that they have been derived from the Sagan - Coleman analysis.

It is evident from Table I that in all cases the requirement on accidental impact p'_T is essentially the same. To affect this parameter it would be necessary to reconsider the value of planetary contamination probability P_c.

TABLE I

ITEM	Description	Planetary Contamination Parameters			Biological Judgment Parameters		Allocation Parameters		Implementation Parameters			
		P_c	n_L	n_U	p_G	p'_G	$n_L P$	$n_U P'$	p_R	p_N	p'_R	p'_T
1	Sagan and Coleman	10^{-3}	$667^{(1)}$	30	10^{-2}	1	$5x10^{-4}$	$5x10^{-4}$	1	$2x10^{-4}$	1	$4x10^{-5}$
2	Corrected values of Sagan and Coleman (2)	10^{-3}	$667^{(1)}$	30	10^{-2}	1	$5x10^{-4}$	$5x10^{-4}$	1	$7.5 x10^{-5}$	1	$2x10^{-5}$
3	COSPAR	10^{-3}	667	17	10^{-2}	1	$5x10^{-4}$	$5x10^{-4}$	1	10^{-4}	1	$3x10^{-5}$
4	Present Model case (a)	10^{-3}	70	30	10^{-3}	1	$5x10^{-4}$	$5x10^{-4}$	1	$7x10^{-3}$	1	$1.7x10^{-5}$
5	Present Model case (b)	10^{-3}	70	30	10^{-3}	1	$7x10^{-5}$	$9.3x10^{-4}$	1	10^{-3}	1	$3.1x10^{-5}$

(1) This value of n_L is not explicitely given in the Sagan-Coleman analysis. It has been calculated using data provided on the desired number of successful experiments and the various success probabilities, and by adding a probability of 0.9 that the capsules launched will successfully land on Mars.

(2) Differences between values in this item and item 1 stem largely from the erroneous use by Sagan and Coleman of logarithms to the base 10 rather than base e as called for in their formulation.

The rationale for favoring unsteril[illegible] vehicles by a factor of 31, as is done is case (b), may be illustrated as [illegible]s. Assume that p_N is given by the exponential population reduction fromula [illegible] a constant temperature

$$p_N = N_o \cdot 10^{-t/D} \qquad (9)$$

Where D is the time required to r[illegible] the population of a single species by 90% and t is the sterilization time (at a [illegible]nt sterilization temperature). Let t_a denote the required sterilization time [illegible]sponding to case (a) in Table I, i.e. $p_N = 7x10^{-3}$. It is readily calculated from equation (9) that if $N_o = 10^8$,

$$\frac{t_b - t_a}{t_a} = 0.084 \text{ or } 8.4\%$$

An 8.4 % increase in sterilization time, say from 18.3 hours to 19.8 hours, is not too significant from the point of view of implementation since margins larger than this must generally be allowed in setting engineering requirements for heat sterilizable hardware, i.e. a piece of spacecraft equipment would not be usable if its performance and reliability were to depend upon an 8.4% change in the duration of the stress due to heat sterilization. However, as shown in Table I, case (b) represents an increase by a factor of 1.82 in the allocationfor unsterilized vehicles (p'_T), a number which must be distributed among many different sources of contamination on any one vehicle, e.g. ejecta, emissions, lander recontamination, trajectory bias, etc. In some instances, the availability of this margin in unsterilized vehicle requirements may avoid the need for unnecessarily considering sterilization of portions of an otherwise unsterilized vehicle.

It is to be noted that implementation of requirements for sterilized landers involves parameters shown, in an illustrative manner, in equation 9, i.e. No, t and D. No and t are largely independent of the considerations which enter into the formulation of planetary quarantine requirements. However, this is not the case for D. In general, D defines the resistance of a specific species to heat sterilization and its numerical value must be obtained in the laboratory using a particular recovery (culture) medium to test for viability after the application of heat. The question thus arises as to which culture medium is most appropriate, since, clearly, different D values would be obtained depending upon the medium used. The only available guideline is the value which is selected for p_G. Since p_G represents the probability that an organism previously subjected to heat sterilization will grow on the surface of Mars or in its atmosphere (and spread over a significant portion of the planet), the culture medium used to establish the D values must represent our estimate of the most favorable growth conditions possibly existing on Mars. Specifically, when choosing a culture medium we would be estimating that there is, say, a 10^{-3} probability, i.e. a small but finite probability that an organism released from the lander will find a growth medium on Mars equivalent to that of the laboratory culture medium which has been selected.

The rationale for favoring unsterilized vehicles by a factor of 31, as was done in case (b), may be illustrated as follows. Assume that p_N is given by the exponential population reduction formula at a constant temperature

$$p_N = N_o \cdot 10^{-t/D} \qquad (9)$$

Where D is the time required to reduce the population of a single species by 90% and t is the sterilization time (at a constant sterilization temperature. Let t_a denote the required sterilization time corresponding to case (a) in Table I, i.e. $p_N = 7x10^{-3}$, and t_b the sterilization time associated with case (b). It is readily calculated from equation (9) that if $N = 10^8$,

$$\frac{t_b - t_a}{t_a} = 0.084 \text{ or } 8.4\%$$

An 8.4 % increase in sterilization time, say from 18.3 hours to 19.8 hours, is not too significant from the point of view of implementation since margins larger than this must generally be allowed in setting engineering requirements for heat sterilizable hardware, i.e. a piece of spacecraft equipment would not be usable if its performance and reliability were to depend upon an 8.4% change in the duration of the stress due to heat sterilization. However, as shown in Table I, case (b) represents an increase by a factor of 1.82 in the allocationfor unsterilized vehicles (p'_T), a number which must be distributed among many different sources of contamination on any one vehicle, e.g. ejecta, emissions, lander recontamination, trajectory bias, etc. In some instances, the availability of this margin in unsterilized vehicle requirements may avoid the need for unnecessarily considering sterilization of portions of an otherwise unsterilized vehicle.

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