FIRST QUARTERLY PROGRESS REPORT
PLANNING, EVALUATION, AND ANALYTICAL STUDIES IN PLANETARY QUARANTINE AND SPACECRAFT STERILIZATION

Prepared under

Contract NASW-2062

For

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Headquarters
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by

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I. INTRODUCTION AND SUMMARY

This report covers progress for the period ending May 30, 1970. In accordance with the terms of contract NASW-2062, it reports status and progress on five tasks, viz.,

- Quarantine Document System for Planetary Flight Missions — Task 2
- Planning of Supporting Technology Transfer — Task 4
- Analysis of Microbial Release Probabilities — Task 5
- Analytical Models for the Design of Heat Sterilization Cycles — Task 6
- Organic Constituent Inventory for Planetary Flight Missions — Task 7

Quarantine Document System for Planetary Flight Missions — This information system is intended to provide rapid access to material relating to, (a) formulation of Planetary Quarantine requirements for flight missions, and (b) the review and approval of flight project quarantine plans. The design of a rapid response information system was completed during this reporting period; it was utilized in relation to the review of Planetary Quarantine plans for Mariner Mars '71 and Viking '75.

Planning of Supporting Technology Transfer — The principal purpose of this task is to facilitate the effective transfer into flight programs of supporting technology developed by the NASA Planetary Quarantine Office. Activity during this reporting period included participation in the review of:

- Methods of bio-load estimation and prediction
- Estimation of the probability of in-flight recontamination
- Combined thermal radiation sterilization

Analysis of Microbial Release Probabilities — The objective of this task is to develop the analytical and quantitative basis for including the probability of release in flight project determination of heat sterilization requirements. Progress to-date included the performance of a sensitivity analysis of parameters which define microbial release in the course of spacecraft impact and subsequent aeolian erosion. Results were presented at the April Planetary Quarantine Seminar and at the May 1970 meeting in Leningrad, USSR of the COSPAR Panel on Planetary Quarantine.

Analytical Models for the Design of Heat Sterilization Cycles — This task relates to the development and updating of analytical models to facilitate flight project implementation of planetary quarantine requirements through the utilization of new laboratory data or technology. Work performed during the reporting period included:

- Thermodynamic studies in heat sterilization to develop guidelines for establishing sterilization oven temperature profiles
- Extension of the previously developed microorganism moisture diffusion model for applicability to buried and mated sources

Organic Constituent Inventory for Planetary Flight Missions — The objective of this task is to establish the feasibility and general characteristics of an information system on organic/chemical contamination of the planets. Effort during this reporting period included:

(1) Identification of, and initial contacts with, members of the Viking '75 Project Science Team to ascertain requirements for the control of organic/chemical contamination.

(2) Identification of, and initial contacts with, sources of information on planetary probe materials to ascertain concentrations of organic/chemical contaminants identified above.

Details regarding these five tasks are presented in the following sections.

II. QUARANTINE DOCUMENT SYSTEM FOR PLANETARY FLIGHT MISSIONS

(1) Objective

The objective of this task is the design, implementation and operation of a storage-retrieval system of information pertinent to the review of flight project quarantine plans and their subsequent modifications because of changes in requirements or requests for deviations. A rapid response capability is required so that replies to inquiries can be effected within one working day. Further, the system is to be compatible with the planetary document library at the George Washington University and with flight project information systems, to eliminate unnecessary duplication and to permit rapid reference and information access.

(2) Progress

The approach adapted in this task involves the following steps:

(a) Define the scope of the collection

(b) Identify document sources

(c) Determine the uses of the system and identify its users

(d) Establish compatibility requirements

(e) Design the system

(f) Implement and operate the system

In developing guidelines for determining the scope of the collection we reviewed the role and responsibilities of the Planetary Quarantine Officer in implementing quarantine constraints. The documentation requirements of NHB 8020.12 and other related NASA policy documents were reviewed. The reporting plans of planetary projects were studied through flight project Planetary Quarantine plans. Document types were selected to enable the Planetary Quarantine Officer to efficiently oversee all operations related to the management of planetary flight missions. These include: specifications, requirements, modifications, deviation requests and status reports.

The principal sources of documentation have been identified. However, the routine acquisition of documents from these sources remains to be systematized. Those documents readily obtained from other sources will not be acquired and stored.

The primary users of the information system are expected to be the Planetary Quarantine Officer at NASA Headquarters with probable indirect usage by LaRC. It is expected that planetary quarantine status reports will be issued as the information becomes available and the need appears. Additional information gathered from the documents currently in the system has been utilized in several reports already issued in fulfilling Exotech's obligations in the tasks of this contract.

System design has been completed and the system is in initial operation. More than 70 documents have been received, cataloged, indexed, and entered into the system.

All processing is manual, although system design permits automation should it be warranted. The need for abstracting is under review and abstracting procedures have therefore not yet been developed. A thesaurus compatible with that used by the George Washington Biological Sciences Communication Project (GWBSCP) has been developed.

An inquiry record form has been prepared. To date there have been approximately 12 inquiries.

Presentations on the development and operation of the system were made to Code SB personnel at NASA Headquarters on April 10, 1970 and to members of the GWBSCP on May 7, 1970.

Over the next reporting period we anticipate a 100% growth in the collection and a substantial increase in the number of inquiries. Future work includes the preparation of an operating manual and a description of the system.

III. PLANNING OF SUPPORTING TECHNOLOGY TRANSFER

(1) Objective

The objective of this task is to facilitate the transfer of technology developed by NASA's Planetary Quarantine Office into flight project implementation of planetary quarantine and sterilization requirements.

(2) Progress

Activities pertinent to this task included the following:

(a) Support was provided to the NASA Planetary Quarantine Office in conjunction with the review of SRT tasks and their relation to anticipated technology requirements. Our inputs focused on the structuring and categorization of PQ program objectives and the classification of ongoing and/or planned activities relative to this structure.

(b) Participation by S. Schalkowsky in the PQAC subcommittee to review the JPL–Martin bio-prediction model. This included support by Exotech staff personnel (P. Levy and E. Bacon) and the provision of material for inclusion in the detailed report assembled by Dr. B. W. Brown, Jr., Chairman of the subcommittee.

(c) Participation by Exotech personnel in a review by the NASA Planetary Quarantine Office of work done by the General Electric Co., and their proposed program for future undertakings in the area of in-flight recontamination of sterilized spacecraft.

(d) Participation by Exotech personnel in a review of the utilization of thermal-radiation techniques developed by Sandia Corporation for the sterilization of spacecraft equipment.

IV. ANALYSIS OF MICROBIAL RELEASE PROBABILITIES

(1) Objective

The objective of this task is to develop a recommended approach for the inclusion of microbial release probability as a quantitative factor in flight project implementation of heat sterilization cycles. These probabilities are associated with fracturing of planetary probe materials due to high velocity impact on a planet's surface and post-landing (or impact) erosion of such materials during the quarantine period.

(2) Progress

Work on this task began with a sensitivity analysis to determine the relative importance of the different parameters in existing models in terms of their effect on the estimation of release probabilities. Results indicated that further work should be concentrated on the physical models of erosion and fracturing and the survivability of microorganisms subjected to these release mechanisms. Preliminary results of this work was reported at the semi-annual Planetary Quarantine Seminar held in Atlanta, Georgia on April 15-16 1970. This work is further described in a report prepared for, and presented at the May 1970 meeting of the COSPAR Panel on Planetary Quarantine and is included herein as Appendix A. The Panel on Planetary Quarantine has suggested that this report be elaborated in the form of a paper and submitted to the COSPAR Secretariate for circulation to member nations.

Results to date indicate that the probability of release is sensitive to the values of erosion rates, survivability during erosion, and survivability during impact at high and intermediate velocities. Subsequent work is therefore directed to extracting applicable data from the results of impact tests conducted by the Boeing Aircraft Company,[1] including measurement of the degree of break up produced in the samples provided by Boeing. This work is expected to result in quantitative data for the estimation of fracture ratios and survival in the course of high velocity impact. Work is also underway to develop a defensible model of release due to erosion which will

[1] Frazer, S.J.: Survival and Release of Viable Microorganisms After a Hard Impact. Boeing Co. Report #D2-114143-1. May 27, 1968.

also enhance the capability to estimate the survivability of microorganisms released from solids by this mechanism.

Work continuing into the next reporting period will include the preparation of a paper for the COSPAR Secretariate based upon the report of Appendix A.

V. ANALYTICAL MODELS FOR THE DESIGN OF HEAT STERILIZATION CYCLES

The principal objective of this task is to develop new analytical models, or to update existing models, in order to facilitate the flight project implementation of planetary quarantine requirements. These models are intended to bring to bear new laboratory data and/or the results of newly developed technology. During the reporting period, work was performed in the two areas described below.

A. Thermal Dynamics in Heat Sterilization

The purpose of this task is to examine the feasibility and the possible benefits of optimizing the heating profile of the sterilization oven to reduce the apparent penalty in the amount of heat to which exterior locations of a piece of equipment are exposed because certain interior locations have a significant thermal lag. The approach used in this task is to investigate the possibility of using different oven heat profiles so as to minimize the heating differentials between diverse locations within an equipment item at the expense of extended time in the oven. The expected results of this task are quantitative data on the trade-off between extended time and reduction in heating differentials, which may be used by project personnel in specifying sterilization cycles. An alternative statement of the objective is to find that oven heating profile which will

minimize the excess heating of external parts (or parts having low thermal inertia) while meeting the required level of sterilization in the most thermally shielded parts of the spacecraft (or those parts with large thermal inertia).

The initial work in this task was directed to developing an analytical expression for the temperature-time response of a spacecraft component in a sterilization oven. A brief review of measured thermal response data for selected spacecraft components showed that it is reasonable to express a component's internal temperature, at any point during the sterilization cycle, as an exponential function of the exposure time. The governing expression is,

$$\frac{T_s - T}{T_s - T_i} = e^{-t/\tau} \qquad (1)$$

where, T_s = oven temperature

T_i = initial temperature of component

T = internal temperature of component at time t

t = time in terms of hours from start of heat-up phase

τ = thermal time constant of spacecraft component (equivalent to s^2/α where s is component's largest dimension and α is component material's thermal diffusivity).

The initial conditions are specified in terms of a driving temperature, T_s, an initial central temperature for the component, T_i, and the slope dT/dt at a reference time, t. Differentiating equation (1) with respect to time yields:

$$-\frac{dT}{dt} = -\left(T_s - T_i\right)\frac{1}{\tau} e^{-t/\tau} = -\frac{1}{\tau}\left(T_s - T\right)$$

thus, $$\frac{dT}{dt} = \frac{1}{\tau}\left(T_s - T\right) \qquad (2)$$

The slope dT/dt can also be expressed:

$$\frac{dT}{dt} = \frac{T_f - T_i}{\Delta t}$$

where T_f is the internal temperature of the component after Δt hours of heating time, assuming a linear temperature time relationship. Under these conditions,

$$\frac{1}{\tau}\left(T_s - T_f\right) = \frac{T_f - T_i}{\Delta t} \qquad (3)$$

or,

$$\tau = \frac{T_s - T_f}{T_f - T_i}\ \Delta t$$

When applying these analytical expressions to obtain the temperature-time history of a component subjected to a heat sterilization cycle the thermal time constant, τ, is assumed to be single valued throughout the heat-up, hold and cool-down phases of the cycle.

The analytical approach was verified by computing a temperature-time response for cases where measured data were available. The calculated results were found to be in good agreement with the measured values. Computerized calculations were made for a reference heating profile and response curves for time constant values of 0.5 and 1.2 hours, representative of two classes of spacecraft components. (The values of τ and the initial conditions in these computations were selected from actual thermal response data measured in a sterilization oven.) Similar calculations were then made for the thermal responses to variations in the oven temperature profile including alterations to the heat-up phase and the holding phase of the sterilization cycle. The results were plotted and it was found that the

modifications of the oven temperature profile can effectively reduce the difference in the time-temperature exposures of components with unlike time constants as shown by a reduction in the difference between the integrated (or total) lethalities achieved for the two components. These results are shown in the following figures and table.

The lethality of a sterilization cycle is defined by:

$$\eta = \log_{10} \frac{N}{N_o}$$

where N_o and N are the populations of viable organisms at the beginning and end of the cycle, respectively. Lethality expressed as a function of time and temperature is:

$$\eta = - \frac{t}{D_T} \tag{4}$$

where

$$D_T = D_o \, 10^{\frac{125 - T}{z}} \tag{5}$$

D_o is the time in hours required at a temperature of 125^o C to reduce N/N_o by a factor of 10, and z is a constant equal to 21^o C.

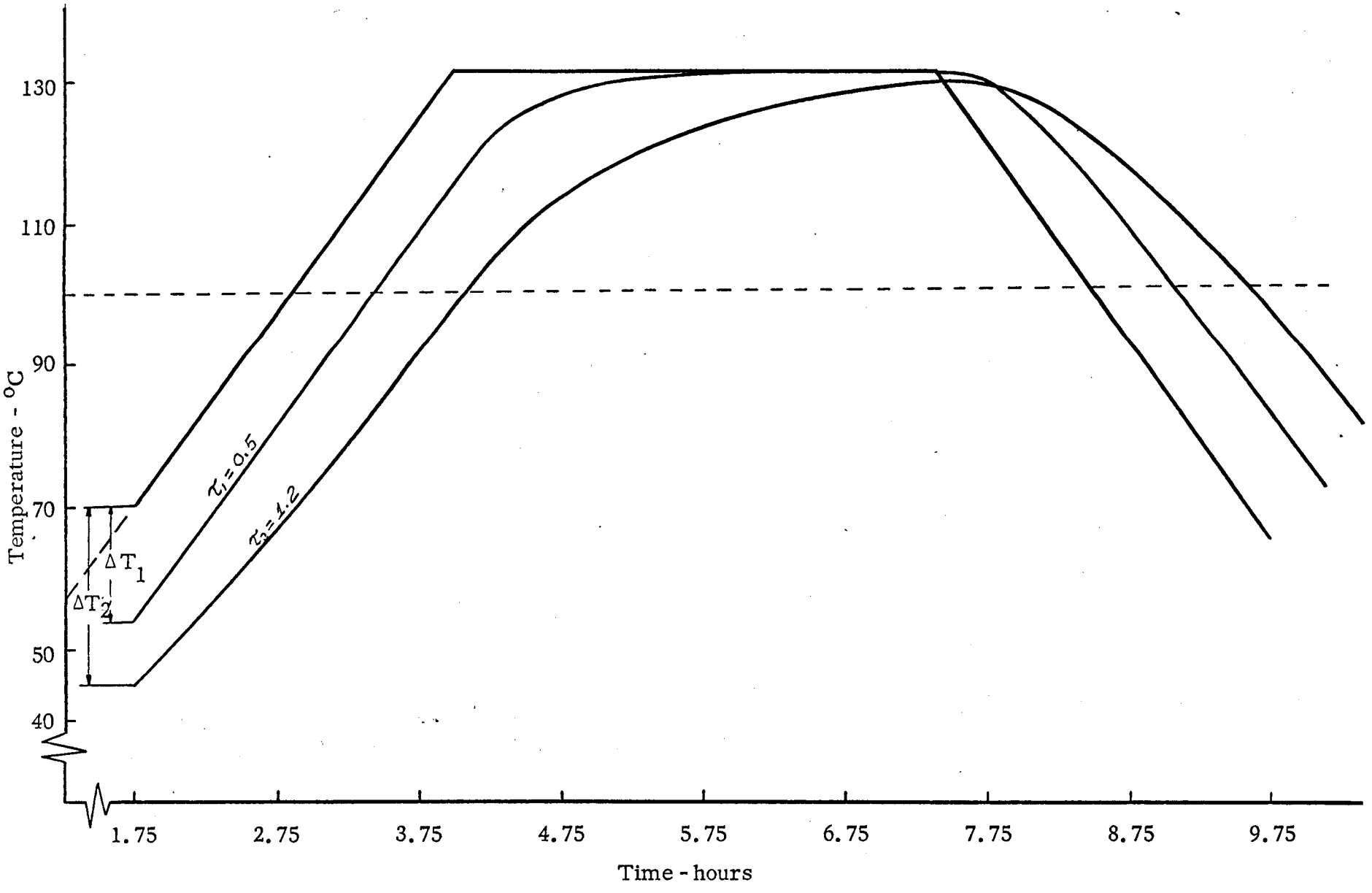
Combining equations (4) and (5) yields the following expression for lethality.

$$\eta = - \frac{t}{D_o} \, 10^{\frac{125 - T}{z}} \tag{6}$$

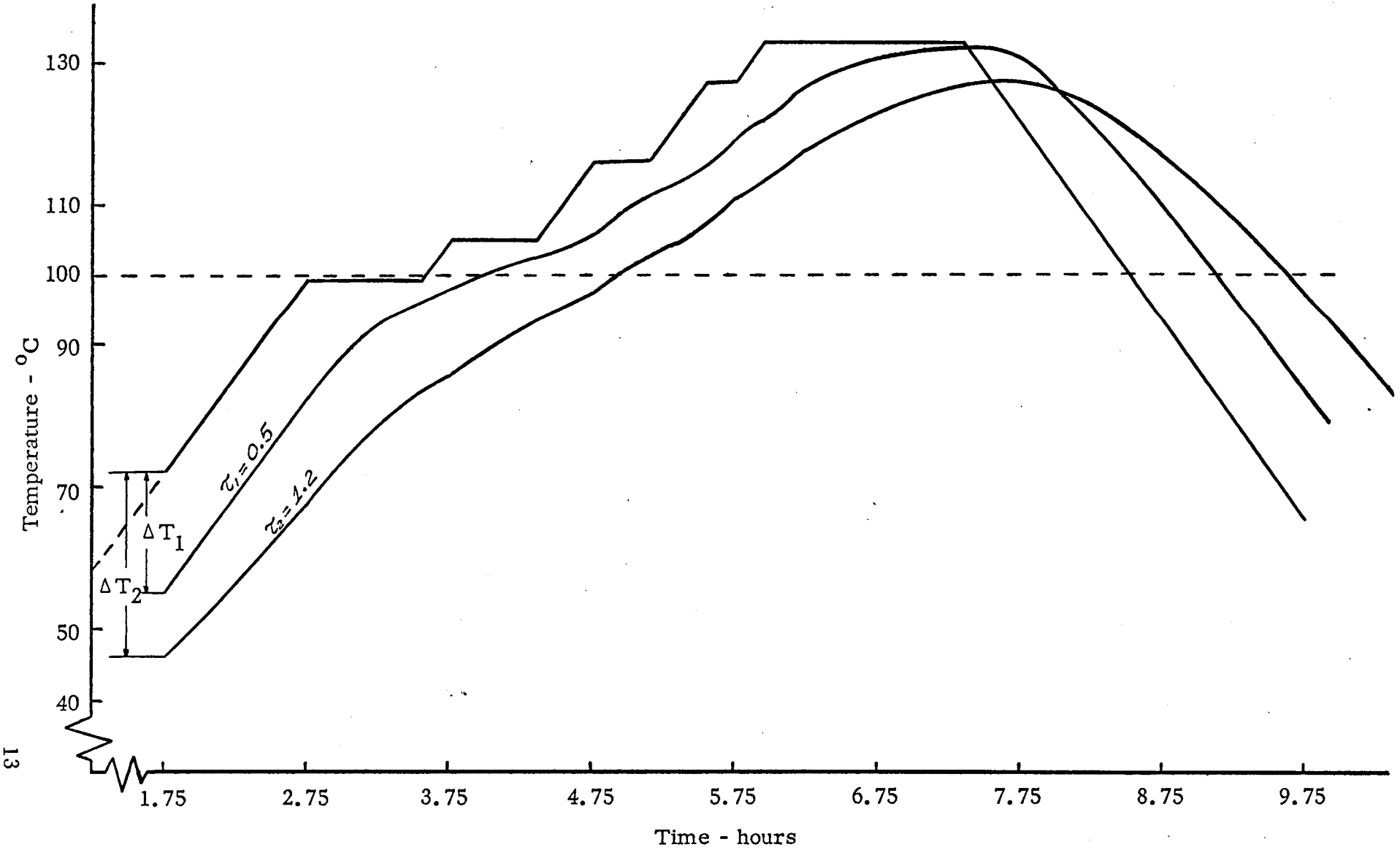
$$\Delta\eta = - \frac{1}{D_o} \, 10^{\frac{125 - T}{z}} \, \Delta t$$

The values used for D_o is 5 hours for organisms buried within a solid and 1 hour for organisms located at mated surfaces of solids. The

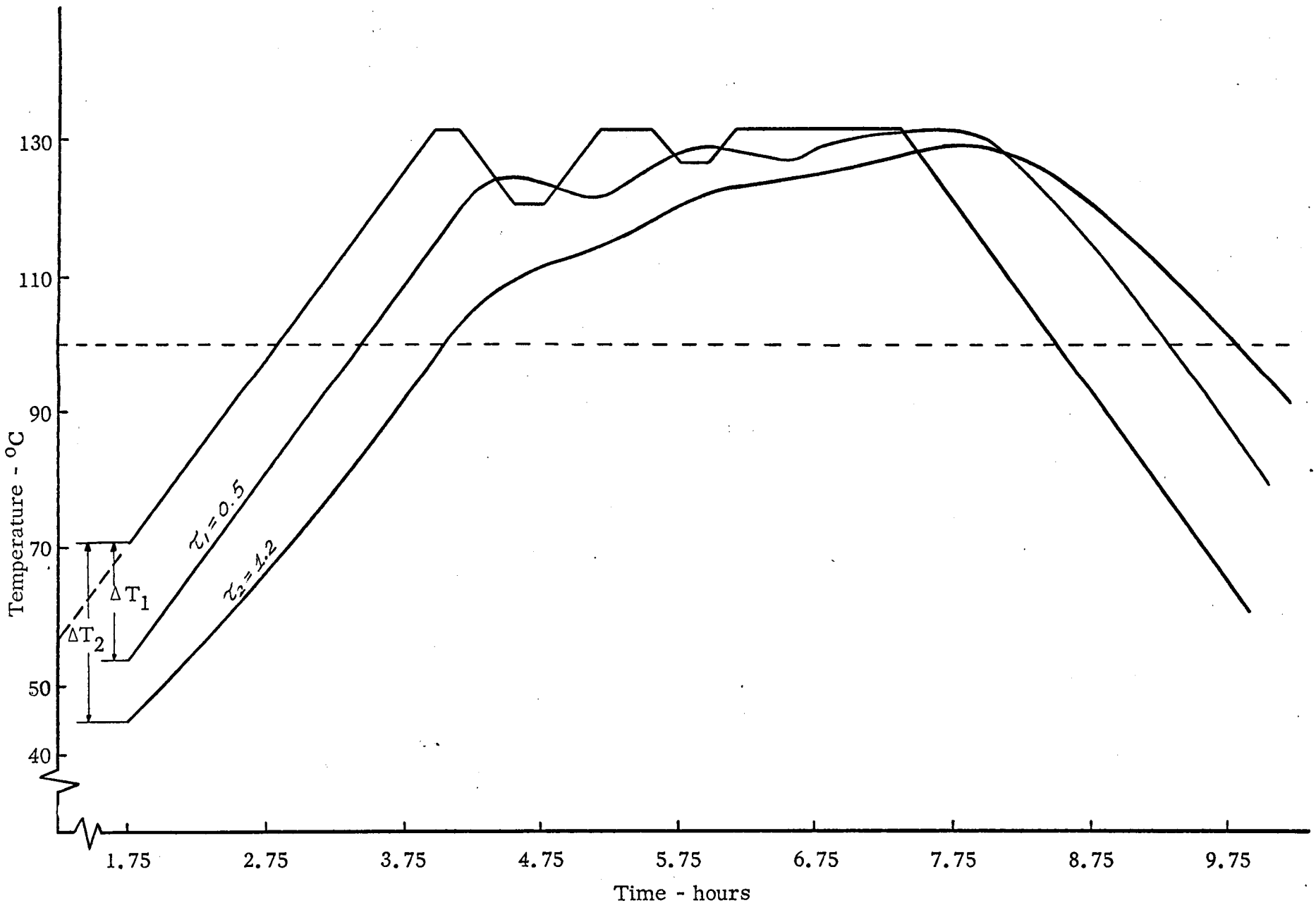
REFERENCE HEATING PROFILE



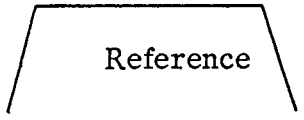
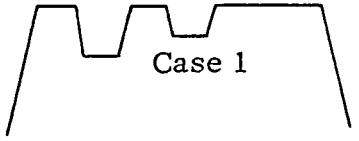
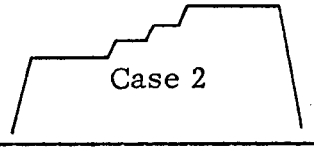
STEPPED HEAT-UP



MULTIPLE COOL-DOWN



COMPARISON OF INTEGRATED LETHALITIES

CASES	τ (hrs)	DECADES REDUCTION* η	$\Delta\eta$
 Reference	0.5 1.2	-8.16 -5.15	3.01
 Case 1	0.5 1.2	-6.53 -4.35	2.18
 Case 2	0.5 1.2	-4.42 -2.71	1.71

* For D_{125} = 1 hr.

Total time for all cases = 11.25 hrs.

temperature T in (6) is taken to be the average of the initial and final temperatures of the heated component in a time interval Δt.

Subsequent effort was directed to obtaining analytical expressions for the temperature differences between components for both varying and constant portions of the oven temperature profile. The following relationships were developed:

1. For varying T_s:

$$\frac{d(\delta T)}{dT_s} = e^{-\Delta t/\tau_2} - e^{-\Delta t/\tau_1} \tag{7}$$

2. For constant T_s:

$$\frac{d(\delta T)}{dt} = -\frac{C_2}{\tau_2} e^{-\Delta t/\tau_2} + \frac{C_1}{\tau_1} e^{-\Delta t/\tau_1} \tag{8}$$

Equation (7) serves as a good indicator of the expected widening of the temperature difference between components when the oven temperature is allowed to increase, while equation (8) helps in defining the time needed to close that gap.

With the benefit of the above information, the analysis was directed to find the best balance between oven heating of low thermal inertia components and total time in the sterilization cycle.

Only the high inertia component is retained, with the oven profile representing the ideal low inertia component. Thus, the temperature lag of the high time constant component is maximized. The oven temperature is increased as rapidly as possible until it reaches a value in the neighborhood

of 90 – 100° C. It is then kept constant for a time t, so that the widened temperature gap between the oven's and component's profiles can be narrowed significantly. The benefit of this holding phase is that the two components will then reach the 125° C plateau, where lethality is accumulated at a reasonably fast rate, with a relatively small temperature gap thus minimizing the overexposure of a low inertia component to this temperature. The rate of increase of the oven temperature past the 90 – 100° C level, as will as the time t, are allowed to vary within set boundaries. The heating cycle will stop when the high inertia component's total lethality reaches 98% of the requirement. The difference in total lethality is chosen as a fair indicator of the closeness of the temperature gap between the two components and a measure of the success or failure of the whole operation. The oven and component temperatures are observed at intervals of 0.2 hours throughout the heat up and holding phases of the sterilization cycle. The use of more than one plateau between 90° – 125° C, as well as on the 125° C level is being investigated as means of improving $\Delta\eta$. Curves will be obtained plotting $\Delta\eta$ versus ΔT, for different slopes of T_s (past 90 – 100° C). These curves along with the total time of the cycle will serve to indicate which is the optimum path that will reduce the temperature gap between the profiles (and, as a result, $\Delta\eta$) and thus prevent the overheating of the low inertia component.

B. Microbial Resistance (Diffusion Model)

During the present reporting period, efforts have been directed toward modifying the existing mathematical diffusion model for applicability to buried sources. This modification is of practical interest inasmuch as microbes buried in solid materials have a large D value for heat sterilization, and hence constitute the controlling factor in the design of sterilization cycles. Through a better understanding of the mechanisms involved in dry heat sterilization of buried micro-organisms it is felt that more realistic sterilization cycles can be defined.

The relation of water activity to D value suggests that large D values for buried sources derive from the fact that the surrounding medium impedes the diffusion of water in the area of the microbe, allowing it to retain its optimum water concentration for longer times. In order to evaluate the water content and diffusion in an impeding medium it is necessary to consider a two region diffusion model. Water transport through the spore and external material can be described by the diffusion equation:

$$D\nabla^2 C = \frac{\delta C}{\delta t}$$

where C is the concentration of water/cm^3, as a function of position and time, and D is a medium dependent diffusion coefficient. The diffusion equation over the two regions is approximated by a difference equation with the interface condition that the flux of water out of the spore equals that into the external material. The boundary conditions require that the derivative of the water concentration with respect to radius r be zero at the center of the spore, and that at some relatively large distance from the spore the concentration must be constant with respect to time.

Consider a spore of radius b to be centered at the origin of a coordinate system. Let C (r, t) denote the water concentration at a distance r from the origin at time t. Further, let D_A and D_B be the diffusion coefficients of water inside and outside the spore, respectively. The diffusion relationship, assumed valid in both regions, is

$$\frac{\delta C}{\delta t} = D\left[\frac{\delta^2 C}{\delta r^2} + \frac{2}{r}\frac{\delta C}{\delta r}\right] \qquad (9)$$

which is subject to the conditions,

$$C(r, o) = F(r) \tag{10}$$

$$C(R, t) = \text{constant} \tag{11}$$

$$\frac{\delta C}{\delta r}\Big|_{r=o} = o \tag{12}$$

$$D_A \frac{\delta C}{\delta r}\Big|_{b^-} = D_B \frac{\delta C}{\delta r}\Big|_{b^+} \text{ (flux across boundary)} \tag{13}$$

where R represents a distance from the origin outside the spore at which the water concentration is assumed constant.

In order to evaluate (9) we use a difference equation approximation. The radius R is divided into M increment Δr, $\Delta r = \frac{R}{M}$, such that the n^{th} incremental point falls on the boundary b. The time increment is set as Δt. The water concentration at any space-time coordinate is then $C(i\Delta r, j\Delta t)$ where i represents the radial increment number measured from the origin and j the time increment number measured from t = 0. For simplicity $C(i\Delta r, j\Delta t) = C_{i,j}$. Equation (9) can then be written in terms of finite differences with the approximations:

$$\frac{\delta C}{\delta t} = \frac{C_{i,j+1} - C_{i,j}}{\Delta t} \tag{14}$$

$$\frac{\delta C}{\delta r} = \frac{C_{i+1,j} - C_{i-1,j}}{2\Delta r} \tag{15}$$

$$\frac{\delta^2 C}{\delta r^2} = \frac{C_{i+1,j} - 2C_{i,j} + C_{i-1,j}}{(\Delta r)^2} \tag{16}$$

Substituting into (9) yields,

$$\frac{C_{i,j+1}-C_{i,j}}{\Delta t} = D_i\left[\frac{C_{i+1,j}-2C_{i,j}+C_{i-1,j}}{(\Delta r)^2}+\frac{1}{i\Delta r}\,\frac{C_{i+1,j}-C_{i-1,j}}{\Delta r}\right] \tag{17}$$

where D_i represents the value of the diffusion coefficient at the i^{th} increment point. Conditions (10), (11), and (12) become,

$$C_{i,o} = F(i\Delta r) \tag{18}$$

$$C_{n,j} = \text{constant} \tag{19}$$

$$C_{o,j} = C_{i,j} \tag{20}$$

and condition (13) becomes,

$$\begin{aligned} 4\pi(b-\Delta r)^2 D_{n-1}\ \frac{C_{n,j}-C_{n-1,j}}{\Delta r} \\ = 4\pi(b+\Delta r)^2 D_{n+1}\ \frac{C_{n+1,j}-C_{n,j}}{\Delta r} \end{aligned} \tag{21}$$

Solving (17) for $C_{i,j}+1$ yields,

$$C_{i,j+1} = D_i\frac{\Delta t}{(\Delta r)^2}\left[C_{i+1,j}-2C_{i,j}+C_{i-1,j}+\frac{C_{i+1,j}-C_{i-1,j}}{i}\right]+C_{i,j} \tag{22}$$

which is valid for all i except i = 0, n, M. If we consider the case where j = 0 only $C_{i,j+1}$ is unknown. Equation (22) can therefore be used to determine all $C_{i,1}$ with the above exceptions. Equations (19) and (20), however,

give us the $j+1^{st}$ point for $i = M$ and 0, and solving (21) for $C_{n,j}$ and replacing j with $j+1$ gives us $C_{n,j+1}$ since C_{n-1} and $C_{n+1,j+1}$ are known from (22). We now have the water concentration throughout the region at $t = \Delta t$. Continuing the process for increasing values of j gives the concentration at any time $t = j\,\Delta t$. In the limiting case where $\Delta t \longrightarrow 0$ and $\Delta r \longrightarrow 0$ the difference equations solution approaches that of the differential equation. Small space and time increments are therefore desirable.

The new model, while less analytic than the previous one, allows greater flexibility in defining the initial water concentration in the spore and the external medium. Also, a computer solution of the difference equation eliminates the necessity of finding a solution to the differential equation. Perhaps a greater advantage is that D, a temperature dependent quantity, can be made a function of time without unduly complicating the calculations, i.e., temperature variations in the sterilization process can be considered. Various numerical methods are at present under test to determine the accuracy and limitations of this approach.

VI. ORGANIC CONSTITUENT INVENTORY FOR PLANETARY FLIGHT MISSIONS

(1) Objective

The purpose of this task is to develop alternative practicable designs for an information system concerning Earth-originated organic/chemical contamination on other planets. The task is responsive to the Space Science Board recommendation that accountability of such contamination be established and maintained in order to minimize the risk of confusing the results of analysis of planetary material samples.

(2) Progress

Work on this task began in the last month of the period covered by this report with initial efforts directed to:

(a) Identification of the information requirements of the Viking project science team on organic/chemical contamination of terrestrial origin on Mars during (and possibly subsequent to) the quarantine period.

(b) Identification of the information resources for planetary probe materials information in both U. S. and foreign projects.

The sources of information needed to complete these identification efforts have been identified and informal communications have been established. Detailed inquiries are now being prepared to send out to selected members of the Viking Project Science Team.

During the next reporting period the subtasks cited above will be completed and alternative methods for meeting the information requirements will be examined. Work will also be initiated on an examination of relevant aspects of dispersion and subsequent chemical reactions of contaminants delivered to planetary surfaces.

APPENDIX A

"Estimation of Microbial Release Probabilities from a Martian Lander"

ESTIMATION OF MICROBIAL RELEASE PROBABILITIES FROM A MARTIAN LANDER*

by

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Prepared for presentation at the May 1970
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ESTIMATION OF MICROBIAL RELEASE PROBABILITIES FROM A MARTIAN LANDER

This paper summarizes the current status in estimating the probability that terrestrial organisms contained in, or on, a Martian landing spacecraft will be released onto the surface of the planet in a viable state. The relevance of obtaining such an estimate resides in the fact that to the extent that a probability of less than unity can be assigned to the release event, to the same extent the heat sterilization and/or microbial control procedures can be relaxed.

The overall planetary quarantine constraint, in the context of which this analysis must be made, is summarized in Figure 1. It is convenient to consider separately the parameters which define the requirement, or constraint, as shown in Equation 1, and to develop the additional factors separately which enter into the implementation of the constraint. The constraint is shown as m(r) and signifies an allowable mean number of viable micro-organisms which can be released onto the surface of the planet consistent with, (1) the prescribed allocation, P(N), for the probability that the lander will contaminate the planet, and (2) the estimate probability P(g) that any one micro-organism released on the surface of the planet will subsequently grow, spread and lead to planetary contamination. Based upon currently accepted values for P(N) and P(g), the allowable mean number of released micro-organisms is $m(r) = 10^{-3}$. Needless to say, this value requires that no viable organisms be released from a single lander but suggests that in a hypothetical sample of a thousand landers, one micro-organism would be released, on the average.

Equation 2 in Figure 1 indicates how the m(r) constraint is further developed for the purpose of estimating the effect of the probability of microbial release. Thus, for the present purpose, we are considering the following four locations of micro-organisms on and in the spacecraft:

(1) exterior surfaces of the lander,

(2) interior surfaces of the spacecraft,

(3) micro-organisms trapped between mated surfaces of equipment, and

(4) micro-organisms which are contained, i.e. "buried," in materials.

For each of these categories we are concerned with the product of (1) the number of viable organisms in the category which arrive to the planet surface (these are denoted as m with the appropriate subscript), and (2) the probability P(r) than any one randomly selected organism in this category will be released onto the planet surface in a viable state. The sum of the above products in the four locations enumerated above must not exceed the prescribed value of m(r).

The various factors which are currently being considered in the estimation of the probability of release are summarized in Figure 2. As shown in this figure, release due to the impact of the spacecraft and subsequent fracture, as well as release due to aeolian erosion are a part of the analysis. In the impact-fracture category one of the first factors to be considered is the velocity at which the spacecraft impacts the planet and the associated probability that this velocity will occur. We are at present considering three specific velocities: (1) the nominal landing velocity, denoted as V_S, (2) a non-nominal velocity, denoted as V_I, which would result from failures in the landing sequence from orbit, and (3) a high impact velocity, denoted as V_H, which would result if a failure occurs in midcourse and results in a direct impact trajectory to the planet.

The fracture ratio, f, is intended to characterize the degree of break-up that would result at a particular impact velocity. It is defined as the ratio of newly exposed areas of spacecraft materials over the initial volume of material being considered. In the chart of Figure 2 we have identified the two fracture ratios corresponding to the impact velocitied V_I and V_H.

Since impact at non-nominal velocities entails the release of substantial amounts of energy, it might be expected that some of this energy would also

contribute to the destruction of micro-organisms in the course of fracturing; this could, for example, be the result of the heat generated at impact. To allow for this event, a probability of surviving impact-fracture is also incorporated in the analysis and is associated separately with the two velocities V_I and V_H.

The current model for release due to aeolian erosion is a relatively simple one. As shown in Figure 2, we identify a parameter e_k to denote the rate at which material is being eroded. This parameter has as its unit of measure a linear depth per unit time; for example, 10^{-6} meters (one micron) of material per year. The interrelationship between release due to fracture and due to erosion is indicated by the dotted line connectors in Figure 2 to show that the fracture ratio enters into both models. This is necessary since the amount of material eroded clearly depends upon the area exposed to erosion and this is a function of the amount of break-up that might have occured in the course of impact. Included in the aeolian erosion model is a fracture ratio for the velocity V_S, which is the nominal landing velocity. This is not a true fracture ratio since no break-up is anticipated in the course of nominal landing, i. e. it is expected that the spacecraft will have been designed to withstand the designed landing velocity without break-up. However, for purposes of estimating erosion, it is necessary to also define an area to volume ratio which would be subject to erosion even in the event of nominal landing conditions. The fracture ratio $f(V_S)$ serves this purpose.

The time during which spacecraft material would be subject to erosion is taken to be the prescribed period of planetary quarantine.

Parralleling the case for impact-fracture, allowance is made for the possibility that if the erosion mechanism is of substantial energy, it could also cause the destruction of micro-organisms while it is causing their release. A probability of surviving the erosion process is therefore also incorporated in the erosion model.

Our current status of quantitative data for the various parameters considered in the estimation of the probability of microbial release is summarized in Figure 3. The various values for impact velocity and their corresponding probabilities of

occurrence can be derived from mission analysis. A similar comment applies to the exposed area/volume ratio $f(V_S)$.

Before considering the numerical values of the fracture ratio, it will be useful to define the physical upper bounds for this parameter. For this purpose, it should be noted that in the case of microbial release from buried sources the probability of release is readily approximated by the product $f \cdot \lambda$, i.e. the product of the fracture ratio and the exposure depth coefficient. The expsoure depth coefficient represents the depth below the exposed surface where a micro-organism must be present before it is assumed to have been released in the course of fracture. This parameter has been established experimentally and found to be in the range of 1 – 3 microns; it can also be estimated intuitively as being on the order of the size of the micro-organism which is about 1 – 3 microns. Assuming a value of 1 micron for the exposure depth coefficient, it is readily seen that the fracture ratio would have to be 10^6, in units of 1/meter, for the probability of release to be unity. Thus, a fracture ratio of 10^6 represents pulverization of the material to one micron size. Even a fracture ratio of 10^5 is an extreme condition of break-up since it would require a partitioning of the material into pieces whose size is only a few microns.

Although the above discussion provides some indication of a realistic range of magnitudes for the fracture ratio at the velocities V_I and V_H, experimental data is now available to further facilitate the estimation of the fracture ratio. Specifically, impact tests have been conducted by the Boeing Company during the past year over a range of velocities and using a number of target materials. The pellets used in the tests were also seeded with micro-organisms and a laboratory evaluation was conducted to determine the numbers of organisms which survived impact at the various velocities. The results therefore also provide a basis for estimating the probabilities of microbial survival in the course of fracture/impact.

The greatest current uncertainty in parameter values occurs in estimating the erosion rate and the probability that micro-organisms will survive erosion. Some analysis performed with simplified erosion models, and utilizing conservative estimates of the wind velocities which might be prevalent on Mars and the

amount of particulate matter contained in the wind, lead to values in the order of 10^{-3} meters per year for the erosion rate. This would assume wind velocities on the order of 220 ft per sec. acting continuously, and a particulate concentration of 10^{-4} ounces per cubic foot. (For purposes of comparison, terrestrial erosion rates would be on the order of 10^{-7} meters per year.) As regards the erosion survival probability, no definitive information is as yet available. However, experiments are now being planned to obtain some data on this parameter. The hypothesis that some microbial destruction might be inherent in the erosion process, particularly for high erosion rates, is suggested by data from previous attempts to estimate the internal contamination through mechanical pulverization of materials. In such experiments the recovery of seeded micro-organisms is always less than 100%.

Figure 4 summarizes the pertinent analytical relationships currently used in the estimation of microbial release probabilities and also shows some of the important assumptions which are made in the analysis. Equation 3 indicates the various terms which must be considered for each of the four release probabilities, P(r), in the four source categories of microbial contamination identified for this analysis. Thus, for each source category, it is necessary to identify the conditional release probability corresponding to the three velocity categories utilized in this analysis, i.e. soft landing, impact at velocity V_I, and impact at high velocity V_H. The chart in Figure 4 then summarizes the manner in which each of these conditional release probabilities are evaluated for the four source categories and for each velocity classification.

As shown in Figure 4, micro-organisms contained on the exterior surfaces of the lander are assumed to be released even under nominal landing conditions, i.e. the shock of landing is considered sufficient to free these exterior organisms onto the planet surface; a value of unity is, therefore, assumed for all impact types. Micro-organisms contained on internal surfaces of the spacecraft are assumed to be released with certainty in the event that at least the impact velocity V_I occurs. Thus, this impact velocity, taken to be less than 1000 ft per second, is assumed to be sufficient to break-up the spacecraft to the point where

all micro-organisms contained on internal surfaces would be released. Furthermore, this velocity is also assumed to be adequate to open up all the mater surfaces in the spacecraft, that is, to shear the bolts which might hold sub-assemblies onto the spacecraft structure. Hence, the conditional release probability for mated surfaces, given the impact velocity V_I, is also taken to be unity. The only condition considered in the analysis for the release of mated and internal surface organisms is therefore the erosion of the spacecraft assuming a soft landing. The above simplifications are not appropriate to the release of micro-organisms which are buried within spacecraft materials and a detailed evaluation of the probability of microbial release for this case is therefore included in the analysis, as indicated in Figure 4.

The analytical relationships summarized in Figure 4, in conjunction with the ranges of quantitative data in Figure 3, were utilized to perform a parametric analysis of the probability of microbial release. The principal purposes of this analysis were: (1) to identify those parameters of the system which are sensitive to the estimation of the probability of release, (2) to establish the degree of accuracy to which these parametric estimates need to be known relative to available information, and (3) to identify the benefit which would accrue from new information. Preliminary results of this analysis are summarized below.

To perform the analysis in an orderly fashion, considering the large number of parameters involved, it was first necessary to conduct sensitivity analyses on each parameter separately for the ranges shown in Figure 3. Each parameter was incremented through its range while all other parameters were set at a nominal value. (The nominal value chosen in each case was approximately the mid point of the range.) Results indicated that the probability of release from internal and mated surfaces was, from a practical point of view, insensitive to the range of parameter values considered. However, the probability of release from buried sources did show significant sensitivity when changes in erosion rates, erosion survival, and impact survival at V_I and V_H were introduced. These findings suggested further parametric analysis on the probability of release from buried sources based upon perturbations in erosion rates, erosion survival and impact survival.

Since little experimental data was available on erosion rates and erosion survival, it was decided to use their product as the independent variable.

Although the probabilities of impact at velocities V_S, V_I and V_H can be estimated for a particular mission profile, it appeared desirable to generalize this set of parameter values in the present analysis. Two distinct cases were therefore considered. In Case I conservative impact probabilities were assumed, namely $P(V_S) = 0.75$, $P(V_I) = 0.25$ and $P(V_H) = 0.05$. These values are conservative in the sense that they suggest equipment unreliabilities which would lead to relatively high probabilities for non-nominal impact velocities. Case II assumes a more optimistic view of equipment reliabilities and the values used in this case are $P(V_S) = 0.9$, $P(V_I) = 0.01$ and $P(V_H) = 10^{-4}$.

Figures 5 and 6 summarize the results of sensitivity analyses for the above two cases. Figure 5 is based upon conservative impact probabilities and shows a plot of the probability of release from buried sources as a function of the combined erosion parameter, i.e. the product of erosion rate and the erosion survival probability. This plot would be obtained with any one of the two choices for impact parameters shown under conclusion (b), i.e. there is some sensitivity to the product of fracture ratio at V_H and the probability of surviving fracture at the velocity V_H.

Figure 6 presents similar data for the case of low impact probabilities. In this case the probability of release for buried sources is not sensitive to any of the fracture ratios or the survival probability at V_H, but can be somewhat affected by the probability of surviving impact at the velocity V_I. This is illustrated by the two curves for $g(V_I) = 1$ and $g(V_I) = 0.1$ respectively.

The data shown in Figures 5 and 6 leads to the following conclusions:

1. The probability of microbial release from mated and open surfaces is not a significant factor since, at the most, it can allow a reduction of about 30% in the allowable mean number of micro-organisms released from these sources. This is too small a factor compared to the uncertainty in estimating the initial loads for these microbial sources.

2. The principal uncertainty in estimating microbial release probabilities from buried sources is the product of the erosion rate and the probability of survival during the course of erosion. A value of about 10^{-7} meters per year for this product would lead to a probability of release from buried sources of 10^{-3} to 10^{-4}, depending upon the estimated probabilities of non-nominal impact velocities.

3. Since the "knee" of the curves in Figures 5 and 6 occurs at a value of about 10^{-7} for the combined erosion parameter, values of less than 10^{-7} would not be of significant benefit in reducing the probability of release from buried sources.

4. It is not necessary to have accurate information on the degree of equipment fracturing in the event of impact at non-nominal velocities. Laboratory data already available on the fracture ratio and also on microbial survival during impact appear to be adequate to evaluate these parameters over the range of interest.

Results to date clearly point to the need for more information on erosion parameters. Specifically, it will be necessary to obtain laboratory data on the probability of microbial survival during erosion at high erosion rates. This is necessary since the actual erosion rates on the planet cannot be established with any accuracy and a conservative approach must be taken in the estimation of environmental parameters which enter into the analysis of the rate of erosion. Similarly, it appears desirable to analyse the physical processes of erosion in somewhat greater detail to avoid unnecessary penalties which may be inherent in the simplifying assumption used to-date.

In summary, it appears at present that a microbial release probability from buried contamination sources in the order of 10^{-4} can be considered as a possible

outcome provided it is found that high rates of microbial erosion also lead to significant destruction of the micro-organisms.

REQUIREMENT

$$\frac{P(N)}{P(g)} \geq m(r) \qquad \text{Eq. (1)}$$

- $m(r)$: mean number of viable micro-organisms allowed to be released on the planet (10^{-3})
- $P(N)$: probability that lander will contaminate Mars (10^{-6})
- $P(g)$: probability that random micro-organisms released on surface will grow, spread and lead to contamination (10^{-3})

IMPLEMENTATION

$$m(r) = m_{sx}\, P_{sx}(r) + m_s \cdot P_s(r) + m_m\, P_m(r) + m_b\, P_b(r) \qquad \text{Eq. (2)}$$

m_{sx}, m_s, m_m, m_b ≡ mean number of viable organisms arriving on Mars on external (sx), internal (s), mated (m) surfaces and buried (b) contamination respectively.

$P_{sx}(r)$, $P_s(r)$, $P_m(r)$, $P_b(r)$ ≡ probability that random micro-organisms will be released from sx, s, m and b sources respectively.

Figure 1

PRINCIPAL RELEASE MECHANISMS

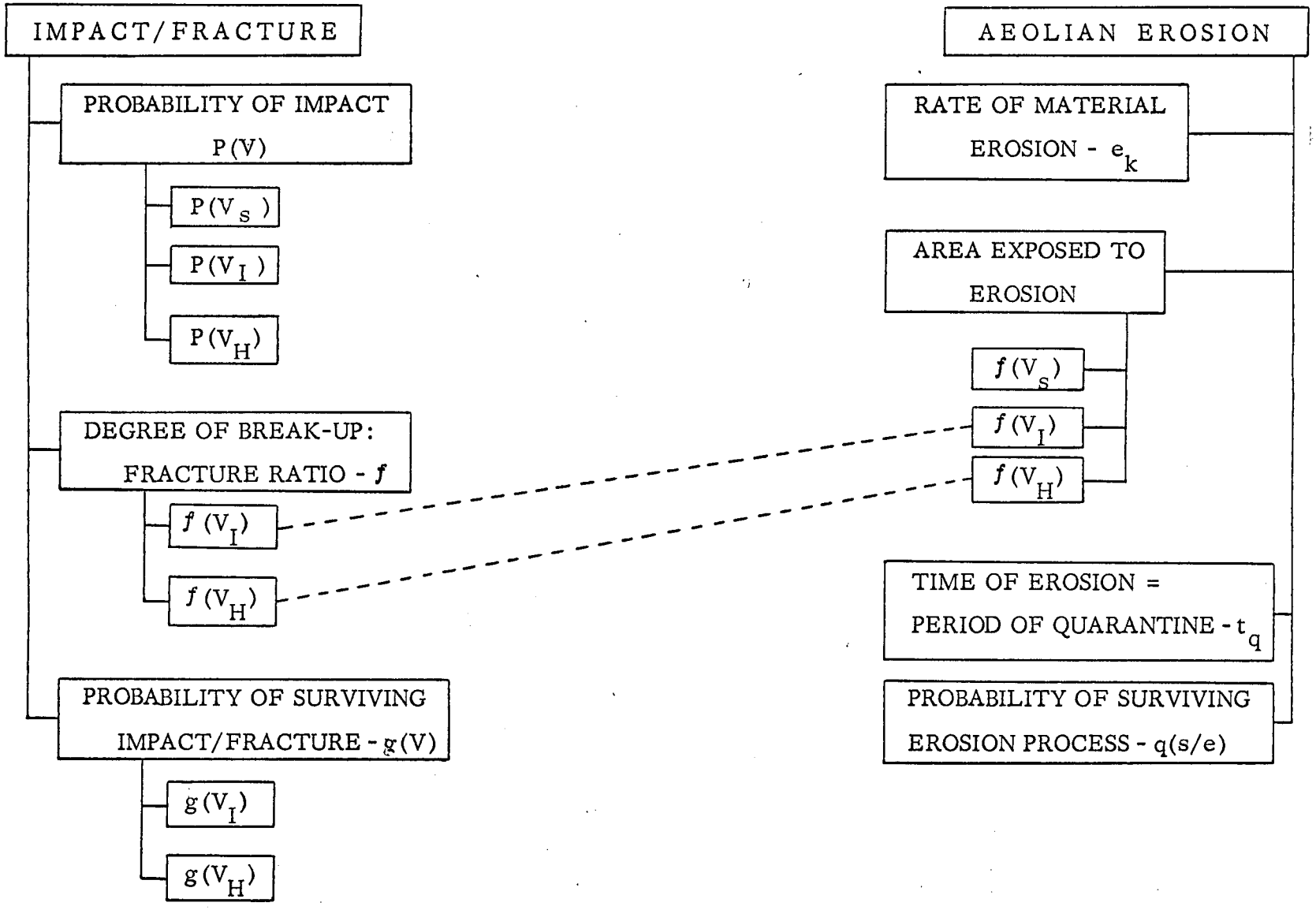

Figure 2

STATUS OF INPUT DATA

PARAMETER	RANGE	COMMENTS
$P(V_s)$ for $V_s < 150$ *f*ps	0.9 - 0.5	obtainable from mission analysis
$P(V_I)$ for $150_{fps} < V_I < 1,000$ *f*ps	0.4 - 0.01	
$P(V_H)$ for $1,000_{fps} < V_H < 3,000$ *f*ps	0.1 - 0.0001	
"$f(V_s)$" - erosion area/volume ratio	4 - 12 $^1/_m$	can be estimated from spacecraft dimensions
$f(V_I)$ - fracture ratio @ V_I	10^2 - 10^4 $^1/_m$	experimental data by Boeing
$f(V_H)$ - fracture ratio @ V_H	10^3 - 10^5 $^1/_m$	plus physical modeling
$g(V_I)$ - impact survival @ V_I	1 - 10^{-3}	
$g(V_H)$ - impact survival @ V_H	10^{-1} - 10^{-4}	
t_q - period of quarantine	17 - 20 years	specified
λ - exposure depth coefficient	1 - 3 μ	known from experimental data
e_k - erosion rate	10^{-3} - 10^{-6}	PROBLEM
q(s/e) - erosion survival	1 - 10^{-4}	no data as yet available

Figure 3

$$P_k(r) = P(V_s)\ P_k(r|V_s) + P_k(V_I)\ P(r|V_I) + P_k(V_H)\ P(r|V_H) \qquad \text{Eq. (3)}$$

$k = sx,\ s,\ m,\ b$

Sub-script	Contamination Category	$P(r \mid V_s)$	$P(r \mid V_I)$	$P(r \mid V_H)$
sx	External Surfaces	1	1	1
s	Internal Surfaces	$q(s/e)e_k\ t_q\ f(V_s)$	1	1
m	Mated Surfaces	$q(s/e)\ e_k\ t_q\ f(V_s)$	1	1
b	Buried Contamination	$q(s/e)\ e_k\ t_q\ f(V_s)$	$g(V_I)\{\lambda f(V_I) + [1-\lambda f(V_H)]\, q(s/e)\ e_k t_q\ [f(V_s)+f(V_I)]\}$	$g(V_H)\{\lambda f(V_H)+[\mid -\lambda f(V_H)]\ q(s/e)\ e_k\ t_q\ [f(V_s)+f(V_I)+f(V_H)]\}$

Figure 4

CASE I: CONSERVATIVE IMPACT PROBABILITIES

Assumption: $P(V_s) = 0.7$; $P(V_I) = 0.25$; $P(V_H) = 0.05$

Conclusions: (a) Not sensitive to f_I, f_s, $g(V_I)$, t_q

$\therefore$ Use conservative values, e.g., $g(V_I) = 1$

(b) For high impact parameters may use

either $g(V_H) = 10^{-2}$ and $f(V_H) = 10^5$

or $g(V_H) = 10^{-1}$ and $f(V_H) = 10^4$

(c) Probabilities of release

$P_{sx}(r) = 1$; $0.1 < P_s(r) = P_m(r) < 0.15$

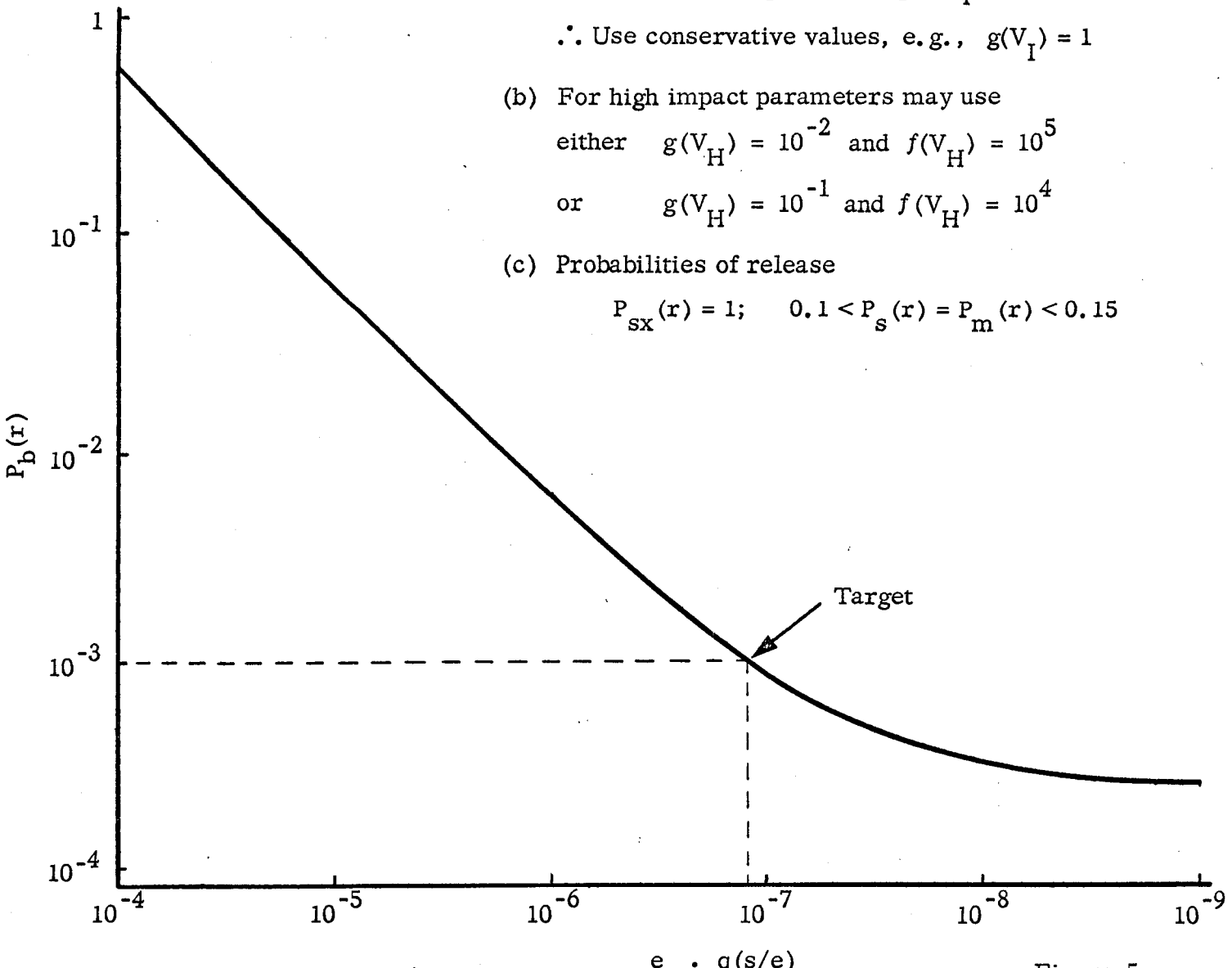

Figure 5

CASE II: LOW IMPACT PROBABILITIES

Assumptions: $P(V_s) = 0.9$; $P(V_s) = 0.01$; $P(V_H) = 0.0001$

Conclusions: Not sensitive to f_H, f_I, f_s, $g(V_H)$, t_q

$\therefore$ Use conservative values, e.g. $f_H = 10^6$

Probabilities of Release:

$$P_{sx}(r) = 1, \quad 0.1 < P_s(r) = P_m(r) < 0.32$$

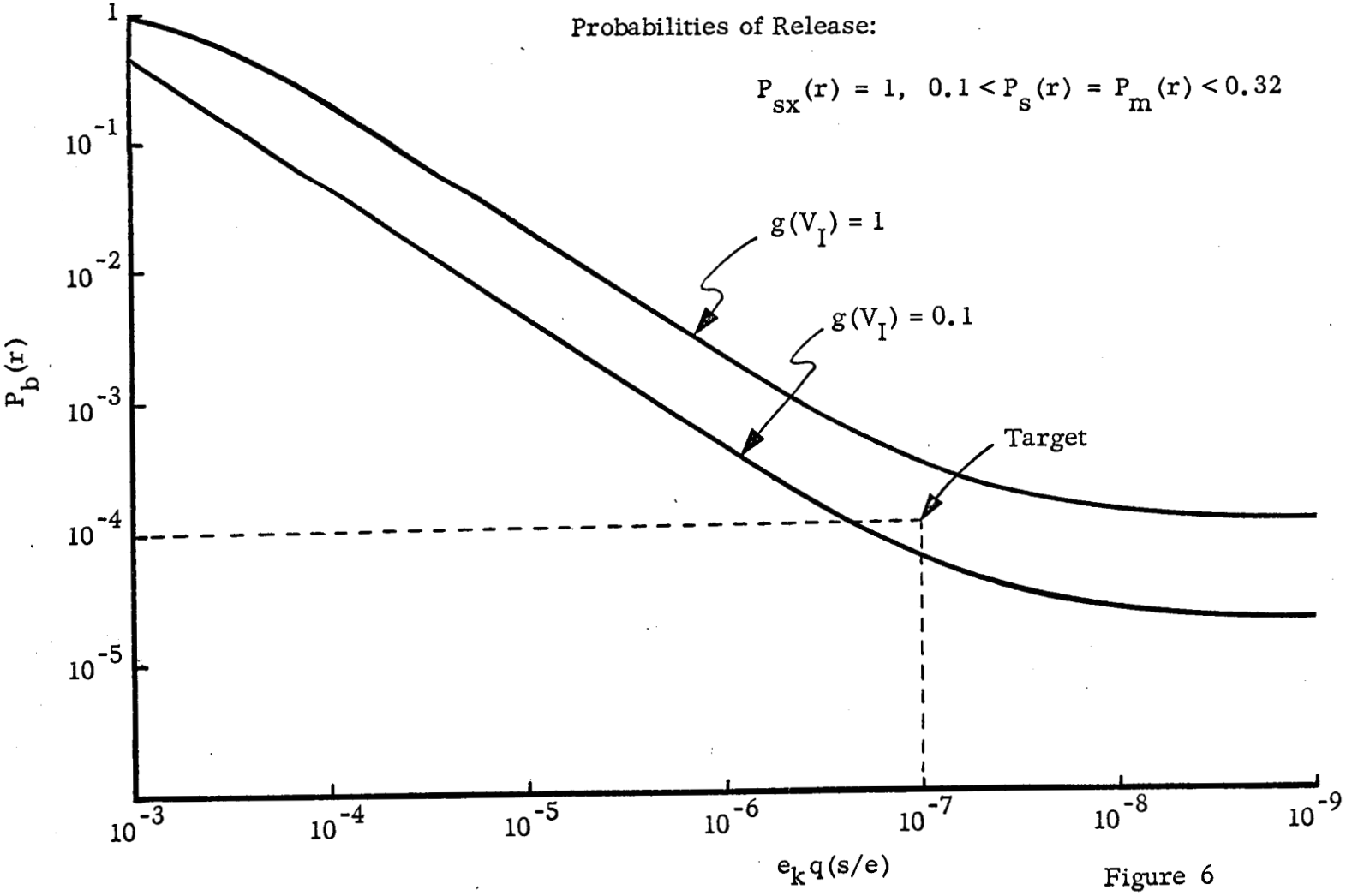

Figure 6