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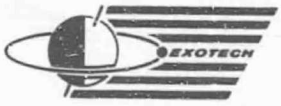
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DEVELOPMENT AND APPLICATION OF A SYSTEM MODEL FOR SPACECRAFT STERILIZATION

Final Report

Contract NASw-1558

for

National Aeronautics and Space Administration
Office of Planetary Programs

August 1969

by

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I. INTRODUCTION

In terms of its effect on a planetary exploration mission, planetary quarantine represents a conflict of goals. For, on the one hand, it is desired to minimize the probability that the planet will be contaminated in the course of exploration. However, in pursuing this goal, it is necessary to impose constraints on engineering implementation of planetary missions which can detract from the probability of mission success. The latter probability could, in principle, be enhanced by appropriate expenditures of resources, but the conservation of resources is also an important goal and, frequently, an over-riding consideration. Hence, quarantine constraints, and alternatives for meeting them, must be examined in sufficient detail to identify those courses of action which compromise either quarantine or mission objectives.

The conflicting goal situation and the complexity of the problem suggest the application of system analysis methods. Complexity derives, in part, from the interdisciplinary scope of the problem in that it encompasses biological, engineering, statistical and economic considerations. Within each of these disciplines, however there is further complexity: complexity of biological considerations derives from the need to selectively apply those aspects of microbiology which are pertinent to planetary quarantine and from the need to do so in the context of spacecraft technology; the complexity of engineering and economic considerations stems from the fact that quarantine constraints pervade spacecraft design, assembly, test and mission logistics; and, statistical complexity derives from the considerable uncertainty associated with many of the key factors which enter into the problem. A solely intuitive approach is therefore not likely to yield answers with sufficient confidence in their validity or their adequacy.

When the technological content of a complex problem is significant, as is the case with planetary quarantine, a major component of systems analysis is mathematical modelling. The program conducted under the subject contract has had as one of its objectives the development

of a mathematical model applicable to the analysis of spacecraft sterilization requirements. This model is defined in chapter II of this report and is further elaborated in Appendix A. The computer program used in the course of this program to exercise the model for specific application studies is described in Appendix B.

It is to be noted that the model developed under this program does not encompass all of the mathematical modelling which is pertinent to planetary quarantine. It is referred to as a sterilization model because it focuses on the implementation of a requirement, imposed on spacecraft which are intended to land on a planet, which leads to sterilization of spacecraft equipment. Furthermore, the detailed development of the model is based principally on heat sterilization practice.

Separate models exist, and are in use, for the formulation of the requirements whose implementation is considered herein (ref. 4,5). Similarly, additional models are being developed, both at Exotech and by others, to deal with particular parameters of the sterilization model. Notable among these are models for bio-load prediction (ref. 6,7) and improved models of microbial survival (ref. 8,9).

The systems model for spacecraft sterilization has been developed with a view toward two types of applications:

(a) to evaluate alternative approaches to the implementation of sterilization requirements in the context of spacecraft development practices

(b) to establish potential benefits and to formulate priorities in the conduct of R&D programs which aim at reducing the uncertainties associated with model parameters.

The model developed under this program has been applied in both the above categories to deal with questions of current interest. Some of these studies were reported earlier in the program, whereas the more recent application studies are described in Chapters III, IV and V of this report.

In August of 1968 Exotech submitted an interim report under the subject contract titled "Effect of Microbial Release Probabilities on Spacecraft Sterilization Requirements" (Exotech document number TR-SR - 034). In a broad sense, this interim report parallels the scope of work described herein. Thus, it contains the formulation and development of a systems model, describes the parameters involved, and utilizes the model for an application study. It differs, however, in the following respects:

A. The systems model described in the interim report represents an earlier version which is extended, refined and more adequately justified in the present report. Furthermore, the present model is formulated to be applicable to more general problems so as to enhance its future usefulness.

B. The interim report represents an initial attempt at an evaluation of the probability of microbial release in terms of its implications on spacecraft sterilization requirements. It served the purpose of identifying areas of supporting research and technology which could be potentially beneficial to the planetary quarantine program. However, the formulation of microbial release probabilities in the interim report is of more limited scope than that which has evolved from subsequent work.

C. The interim report dealt with an applications study at a time when microbial resistance values (the D values) were not yet firmly fixed. One of the purposes of the application study reported therein has therefore been to evaluate the implications of a range of resistances for microorganisms on open surfaces, mated surfaces and buried contamination on spacecraft sterilization requirements in general, and priorities for R&D in particular. Since then, microbial resistances have been firmed-up and the values used herein of D^{125}= .5 hours for open surfaces, D^{125}= 1.0 hours for mated surfaces and D^{125}= 5 hours for buried contamination

were established by NASA Planetary Quarantine Office as a basis for developing spacecraft sterilization requirements in the immediate future.

The data contained in the interim report is of current interest principally to the extent that it deals with the effect of different microbial resistance values on procedures for the implementation of quarantine constraints. In particular, it is of interest to note that many of the results to be reported herein would be greatly modified if microbial resistance values were to change from the currently accepted ones. For a discussion of the detailed implications of such changes in the D values, reference is made to the above interim report.

Chapter III of this report considers the different ways in which heat sterilization can be distributed between a terminal cycle, flight-acceptance testing and piece-part testing. This applications study is pertinent to the implementation of heat-sterilization requirements on a flight mission in that it deals with, among other things, the minimization of terminal sterilization time in general, and the avoidance of heat penetration into materials during the terminal cycle in particular.

Chapter IV considers the effect of various parameter values on heat sterilization requirements and, as such, offers guidelines for the conduct of R&D programs as well as the needed emphasis on various implementation practices in terms of their benefit in reduced heating times.

The problem of arriving at a defensible estimate of microbial release probabilities is treated in ChapterV, where a summary of recent progress is provided.

The above applications studies are not unrelated. Thus, the conclusions reached for a preferred approach to the distribution of heating times (Chapter III) becomes the basis for limiting and interpreting the sensitivity of sterilization times to model parameters

(Chapter IV). Similarly, the estimation of microbial release probabilities (Chapter V) is treated in the range of values which the preceding sensitivity study has established. These interrelations are further highlighted in the summary and conclusions of Chapter VI.

This program was carried out by personnel of Exotech's Systems Research Division under the technical direction of Samuel Schalkowsky. Principal participants were R.C. Kline, E. Bacon, P. Randolph, L. Woodall and I. Jacoby.

Work reported herein is closely allied to the development of analytical techniques for planetary quarantine being carried out by Exotech for the NASA Planetary Quarantine Office under contract NASW-1734; the principal area of overlap is in development of models for the estimation of microbial release probabilities, covered herein in Chapter V.

The conduct of this program has greatly benefited from the technical direction provided by Mr. Paul Tarver of the NASA Office of Planetary Programs and also by Mr. Richard Kee, who was technical monitor during earlier phases of this contract. The authors also wish to gratefully acknowledge the assistance provided by Lawrence B. Hall and Dr. Donald Fox of NASA Headquarters, and Leo Daspit and Otis Childress of the Langley Research Center, in the form of discussion and constructive criticism of the applications studies described herein. However, this should not be misconstrued as an implication of their endorsement of conclusions stated herein.

II. PLANETARY QUARANTINE IMPLEMENTATION MODEL

Planetary quarantine requirements for an individual mission take the form:

$$P(N) \leq R, \tag{1}$$

where P(N) denotes the probability that the mission contaminates the planet and where R denotes a prescribed maximum allowable value for P(N). [Values for R currently being considered vary between 10^{-6} and 10^{-5}, depending upon the planet in question and the anticipated number of missions to the planet.]

To assure that the requirements specified in expression (1) are met for any given mission, it is necessary to first prescribe an acceptable operational definition of P(N). This can be accomplished by means of the following definition:

> A planet will have been contaminated if one or more micro-organisms of terrestrial origin are deposited by the lander onto the planet's surface or into its atmosphere and subsequently germinate and spread during a specified (quarantine) period of time.

In order to apply the quarantine requirements of expression (1) to a particular mission it is necessary to express P(N) in terms of pertinent mission hardware, flight, biological and other environmental parameters. Appropriately accomplished, this will provide a mechanism or model for use in determining and evaluating alternatives for meeting the requirements. It is important to note the desirability of a model which is applicable to many aspects of implementing quarantine requirements, e.g., (1) establishing R & D priorities related to planetary quarantine, (2) establishing general approaches or guidelines to meeting requirements, (3) establishing the detailed mechanics of meeting requirements for a particular mission and (4) establishing adherence to quarantine requirements. The model

presented herein was developed with a view to these and other applications.

Because of a lack of sufficient information to develop and implement the model beyond a certain level of detail, numerous simplifications are introduced. In all cases, however, the simplifications are made "in the conservative direction", i.e., if properly applied, the derived representation of P(N) will in all instances be greater than P(N) itself. Hence, if the derived representation is constrained to be no greater than R, then P(N) will certainly be no greater than R. In adopting this position, however, it may turn out that application of the resulting model yields results which are more severe than would be necessary if additional information was available and included.

A. An Intermediate Representation of Quarantine Requirements

On the basis of several reasonable assumptions it can be shown (Appendix A) that

$$P(N) \leq m(r)\ p(g), \tag{2}$$

where m(r) denotes the mean or average number of viable organisms released onto the planet by the lander and where p(g) denotes the probability that a viable organism, randomly released by the lander onto the planet, grows and spreads during the quarantine period. Combining this expression with Expression (1) we see that quarantine requirements will be satisfied if

$$m(r)\ p(g) \leq R. \tag{3}$$

Without mirimizing the difficulty of determining or establishing p(g), there is little that can be done about controlling its magnitude. Therefore, once a value for p(g) has been established, the burden of meeting mission constraints reduces to limiting the mean number of viable organisms which the lander releases onto the planet. Given numerical values for R and p(g), quarantine goals will be met if

$$m(r) \leq R/p(g). \tag{4}$$

By way of illustration, if R is taken equal to 10^{-5} and if p(g) is determined to be 10^{-3}, then the quarantine requirements for an individual lander become

$$m(r) \leq 10^{-2}, \tag{5}$$

i.e., "on the average" no more than one viable organism shall be released onto the planet per 100 such missions.

B. Expansion of m(r)

Evolution of a useful model of planetary quarantine implementation reduces to determining an expression for m(r) which involves pertinent mission hardware, processing, flight path and biological parameters. To this end, the lander is conceptually considered to be a discrete collection of potential "sources of contamination", i.e., individual regions of the lander capable of transporting viable organisms to a planet. Each source possesses a biological loading which is likely to vary in magnitude with time. The time interval of interest begins with the initiation of component manufacture and ends with the termination of the quarantine period. The average number of viable organisms released from the lander onto the planet can be written

$$m(r) = \sum_{k=1}^{n_s} m_k(r) \tag{6}$$

where n_s denotes the number of contamination sources on the lander and where $m_k(r)$ denotes the average number of organisms released from the kth source.

The first step in characterizing the individual sources of contamination is to partition the lander into a collection of "elementary physical units", each unit consisting of a continuous volume of a homogeneous material (e.g., a screw, bolt, length of wire, etc.). Each elementary physical unit can, in turn, be viewed as a collection of

physically distinguishable surface areas and an interior region. Finally, each surface is partitioned into a collection of "elementary subsurfaces", each of which is subjected to homogeneous environments throughout the time interval of interest. For example, if one portion of a given surface is covered or otherwise protected during some time interval and the remainder of the surface is unprotected, then they constitute different elementary subsurfaces. For present purposes, the aggregate of all elementary subsurfaces and interiors of elementary physical units form the total collection of "elementary sources of contamination". The totality of elementary sources is enormous and obviously quite unmanageable. The collection is reduced through the introduction of "source classes" and "equivalence criteria" which permit the identification of numerous individual sources as a single combined source. In particular, two elementary sources are said to be equivalent if their environments are identical at each point in time during the quarantine period. A "source class" is then defined as an exhaustive collection of equivalent elementary sources. For present purposes, expression (6) can then be applied assuming $m_k(r)$ to be the average loading on the kth source class and n_s to be the total number of distinct source classes. Although this interpretation substantially reduces the magnitude of n_s in expression (6), it is still likely to be unmanageably large. Further simplications will be introduced after more detailed representation of the various $m_k(r)$ are presented.

Consider an arbitrarily selected source class subscripted, say, by the index k. It can be shown (Appendix A) that the mean number of viable organisms released from the specified source class is expressible in the form

$$m_k(r) = m_k(I)\ p_k(r) \qquad (7)$$

where $m_k(I)$ = mean number of viable organisms located in the kth source class at the instant of impact

$p_k(r)$ = probability that a randomly selected viable organism located in the kth source class at the instant of impact will be released between that instant and the termination of the quarantine period.

Because of the differing character of possible events occurring before and after impact, the two factors on the right-hand side of expression (7) are further discussed separately.

C. Expressions for $m_k(I)$

By definition, all viable organisms contained in the kth source class experience essentially the same sequence of environments throughout the processing of the mission. Let $\{t_{k\nu}\}_{\nu=0}^{n_I}$ denote the sequence of all times at which events occur which markedly affect the environment insofar as the potential effect on the bio-load of the source class is concerned. It is shown in Appendix A that, under certain uniformity assumptions, the average load in the kth source class at the instant of impact is given by

$$m_k(I) = m_k(0) \prod_{\nu=1}^{n_k} p_k(s_\nu) + \Delta m_k(1) \prod_{\nu=2}^{n_k} p_k(s_\nu) + \ldots \tag{8}$$

$$+ \Delta m_k(n_k-1) p_k(s_{n_k}) + \Delta m_k(n_k) ,$$

where

$m_k(0)$ = Average loading of the kth source class at the beginning of the time interval of interest

$\Delta m_k(\nu)$ = Average increase in loading of the kth source class during the νth subinterval of time

$p_k(s_\nu)$ = Probability that a randomly selected organism, which is located in the kth source class and which is viable at the beginning of the νth subinterval of time, survives throughout the νth subinterval.

For present purposes, expression (8) is reduced to a more manageable and workable form by restricting consideration to a selected few epochs or time points during the pre-impact time interval. This results in no loss of generality but does require subsequent care in the characterization of the various p_ks. The sequence of epochs of interest are as follows:

1. Initialization of a piece - part heat cycle.
2. Termination of a piece - part heat cycle.
3. Initialization of a flight acceptance heat cycle - f/a cycle
4. Termination of an f/a heat cycle.
5. Initialization of a terminal heat cycle.
6. Termination of a terminal heat cycle.
7. Lander impact on the planet.

Further, it is assumed that (1) no recontamination occurs during the application of heat treatments and (2) no die-off occurs except during the application of heat treatments. These assumptions imposed on expression (8) lead to the following simplification:

$$m_k(I) = m_k(0)p_k(s_1)p_k(s_2)p_k(s_3) + \Delta m_k(1)p_k(s_2)p_k(s_3) + \Delta m_k(2)p_k(s_3) + \Delta m_k(3), \tag{9}$$

where at the kth source class,

$m_k(0)$ = Mean load immediately prior to piece - part heating.

$\Delta m_k(1)$ = Mean recontamination between piece - part and f/a heating.

$\Delta m_k(2)$ = Mean recontamination between f/a and terminal heating.

$\Delta m_k(3)$ = Mean recontamination between terminal heating and impact.

$p_k(s_1)$ = Probability that a randomly selected organism, viable at the beginning of the piece-part heat cycle, survives the cycle.

$p_k(s_2)$ = Probability that a randomly selected organism, viable at the beginning of the f/a heat cycle, survives the cycle.

$p_k(s_3)$ = Probability that a randomly selected organism, viable at the beginning of the terminal heat cycle, survives the cycle.

The initial loadings, $m_k(0)$ s, and the recontamination loadings, $\Delta m_k(\nu)$ s, are, at present, taken to be fixed constants; i.e., no further modelling of these quantities is included. In particular applications there are two possible ways of dealing with these constants. If acceptable (maximum) values are known, they are appropriately substituted into expression (9). On the other hand, sensitivity analyses can be performed by appropriately varying the values of these quantities (parameters). This latter approach is useful for evaluating the desirability of future efforts to either (1) determine the values more accurately or (2) reduce the values through engineering changes in the mission configuration.

Parameter models presently assumed for the probabilities of surviving the various heat cycles (i.e., $p_k(s_\nu)$) in expression (9) take the form of exponential survival curves, i.e.,

$$p_k(s_\nu) = 10^{-\frac{t_{k\nu}}{D_{k\nu}}} \qquad (10)$$

where $D_{k\nu}$ denotes the D-value associated with the kth source class

during the νth heat cycle and where $t_{k\nu}$ denotes the effective time at which the heat was applied at 125°C. $D_{k\nu}$ is assumed to be dependent upon the particular heat cycle under consideration. This is necessary in order to allow for, say, a surface which is open through the f/a cycle but which becomes mated prior to the terminal heating. At this point in the development, $t_{k\nu}$ is also assumed to depend upon both the source class and the particular heat cycle. This allows for variability in the thermal lag for the various cycles.

In summary, expression (8) provides a generalized representation of $m_k(I)$, the average loading at the kth source class at the instant of impact. expressions (9) and (10) combine to give the analogous quantity assuming:

1. The possible application of sterilizing heat
2. Exponential die-off during heat treatments
3. No recontamination during heat-cycles
4. No die-off between heat-cycles

The explicit form of this combination is given by

$$m_k(I) = m_k(0)\ 10^{-\left(\frac{t_{k1}}{D_{k1}} + \frac{t_{k2}}{D_{k2}} + \frac{t_{k3}}{D_{k3}}\right)} + \Delta m_k(1)\ 10^{-\left(\frac{t_{k2}}{D_{k2}} + \frac{t_{k3}}{D_{k3}}\right)} + \Delta m_k(2)\ 10^{-\frac{t_{k3}}{D_{k3}}} + \Delta m_k \quad (3) \qquad (11)$$

This expression will be further reduced in a later discussion of specific applications.

D. Expressions for $p_k(r)$

By definition, $p_k(r)$ represents the probability that a randomly selected organism. located at the kth source class and viable

at the instant of impact, will be released onto the planet during the period of quarantine. This definition is meaningful and useful only if the source class is appropriately restricted (Appendix A).

In order to further refine $p_k(r)$, it is necessary to give separate consideration to exterior open surfaces, interior open and mated surfaces and buried or embedded sources of contamination.

For any exterior open surface source of contamination, it is assumed that any viable organisms located thereon will be released immediately upon impact. This somewhat conservative assumption corresponds to taking

$$p_k(r) = 1 \text{ (exterior open surfaces).} \tag{12}$$

For any interior open or mated surface source of contamination, release of a viable organism is assumed to occur if the given surface is directly exposed to the planet as a result of impact. For present purposes, the existence of a critical impact velocity, V_k^c, is assumed for each such source class and has the property that direct exposure will occur if the impact velocity V_I exceeds the critical value. If V_k^c is appropriately selected then a conservative representation of $p_k(r)$ is given by

$$p_k(r) = \text{Prob}\left\{V_I > V_k^c\right\} \tag{13}$$

(Interior open and mated surfaces)

Hence, insofar as release is concerned, interior open and mated surfaces are distinguishable from one another only by the particular critical velocities which are assumed.

Corresponding to any specified impact velocity, V_I, release of a buried organism is assumed to be possible as the result of either (1) fracture or break-up of the source material caused by planetary impact or (2) surface erosion occurring between the instant of impact and termination of the quarantine period. Allowance is also given to

the possibility that viable organisms are destroyed as a result of thermal build-up caused by the impact. Hence, $p_k(r)$ for buried sources of contamination is expressible in the form (Appendix A)

$$p_k(r) = \int_0^\infty P_k(V_I)\, g_k(V_I) \left\{ p_k(r_I/V_I) + \left[1 - p_k(r_I/V_I) \right] q_k(s/e)\, p_k(r_e/V_I) \right\} dV_I \qquad (14)$$

where

$P_k(V_I)$ = Impact velocity distribution function associated with the kth (buried) source class.

$g_k(V_I)$ = Conditional probability that a randomly selected organism from the kth (buried) source class survives impact, given impact velocity V_I.

$p_k(r_I/V_I)$ = Conditional probability that a randomly selected organism, taken from the kth source class and which survives impact, is released as a result of impact, given impact velocity V_I.

$q_k(s/e)$ = Conditional probability that a randomly selected organism from the kth source class and which survives impact, survives erosion mechanism at a particular rate of erosion.

$p_k(r_e/V_I)$ = Conditional probability that a randomly selected organism, taken from the kth source class and surviving impact, is subsequently released as a result of erosion, given impact velocity V_I and given that it is not released as a result of impact, and survives erosion.

For present purposes $g_k(V_I)$ and $p_k(V_I)$ are assumed to be empirically determined functions of the impact velocity and, consequently, no further analytical refinements are offered; $q_k(s/e)$ is assumed to be empirically determined function of the rate of erosion.

It is further assumed that the release of a given buried organism upon impact requires the occurrence of two separate events.

First, the source material containing the organism must be directly exposed to the planet's atmosphere, rather than being located "within" the craft. In addition, the organism is released only if the material is fractured upon impact and the organism is located within a distance, λ, of a newly exposed surface. As developed and discussed in Appendix A, these and other uniformity assumptions lead to the following expression for $p_k(r_I/V_I)$:

$$p_k(r_I/V_I) = \begin{cases} \lambda\ f_k(V_I) , & V_I \geq V_k^c \\ 0 , & \text{otherwise} \end{cases} \qquad (15)$$

where $f_k(V_I)$, the fracture ratio, is equal to the ratio of the surface area, newly exposed through fracturing, to the total volume of source material. Obviously this ratio is strongly related to the impact velocity.

Finally, the release of buried organisms through erosion of the source material is characterized in terms of a constant erosion rate acting on a constant area exposed to the planet's atmosphere, i.e.,

$$p_k(r_e/V_I) = \text{Min} \left\{ 1 , e_k\ t_q\ \frac{\bar{A}_k(V_I)}{V_k} \right\} \qquad (16)$$

where

e_k = Erosion rate associated with the kth source class.

t_q = Time between impact and termination of quarantine period.

$\bar{A}_k(V_I)$ = Surface area exposed to the planet's atmosphere.

V_k = Volume of material in the kth source class.

Moreover, $\bar{A}_k(V_I)$ can be expressed as the sum of

$A_k^{(0)}$ = Area exposed, assuming no break-up of the craft.

$A_k^{(1)}(V_I)$ = Additional area exposed as a result of the source material breaking away from the craft.

$A_k(V_I)$ = Additional area exposed as a result of fracturing of the source material.

Therefore expression (16) can be expressed

$$p_k(r_e/V_I) = e_k t_q \left[f_k^{(0)} + f_k^{(1)}(V_I) + {}_k(V_I) \right] \qquad (17)$$

where

$$f_k^{(0)} = \frac{A_k^{(0)}}{V_k}$$

$$f_k^{(1)}(V_I) = \frac{A_k^{(1)}(V_I)}{V_k}$$

$$f_k(V_I) = \frac{A_k(V_I)}{V_k} \qquad \text{(fracture ratio)}$$

For immediate use of the model, and from an operational point of view, it is convenient to think of the impact velocity distribution as a discrete distribution, i.e., it consists of a particular set of possible impact velocities and for each discrete velocity we assign an a priori probability of occurrence. In such a case the probability of release of a buried organism located on the kth source reduces to the following expression

$$p_k(r) = g_k(V_I)\left[\Sigma\lambda\, p_i f_i + e_k t_q (1-\Sigma\lambda\, p_i f_i)\ (f^o + f^1 \Sigma p_i + \Sigma p_i f_i)\ q_k(s/e) \right] \qquad (18)$$

where the summation is taken over all i such that

$$V_i \geq V_k^c$$

and where p_i is a preassigned probability for the occurrence of the impact velocity V_i.

E. Summary

Expressions (4), (6), (7), (11) through (15), (17) and (18) constitute the generalized planetary quarantine systems model developed for the present study as well as future applications. Further simplifications are made for specific applications and these will be discussed in the following section.

III. DISTRIBUTION OF HEATING TIMES

A. Objective

Sterilization requirements for an individual lander imply appropriate applications of heat to the various portions of the craft. Operationally, there can be three distinct types of programmed, or planned, applications of heat, viz,

1. Preassembly heating of individual piece-parts
2. Flight acceptance heating of individual functional components and subassemblies
3. Terminal heating of the completely assembled lander

A particular combination of these applications, along with specific ions of associated portions of the lander and their heating times, constitutes a "distribution of heating times", i.e., the amount of heat applied to the various portions of the lander during the piece-part, flight acceptance and terminal processes.

One extreme distribution, for example, consists solely of applying a terminal heat cycle which is sufficient, in and of itself, to meet sterilization requirements. This alternative has the advantage of apparent simplicity, i.e., it is a "one-shot" operation. However, it could impose complex, costly and, perhaps, unacceptable constraints on the assembly and test of the lander. Moreover, this procedure is likely to be inefficient in that excessive heat is applied to particular portions of the craft in order to provide sufficient heat at other, thermally less accessible, portions. In addition, it is difficult, if not impossible, to assess the degradation in engineering reliability resulting from the single application of sufficient heat to meet requirements, with attendant limitations on subsequent testing (because of the sterile state of the spacecraft). Finally, costly malfunctions and delay may result from postponing the application of heat until the lander is completely assembled and tested.

A second extreme distribution of heating times consists of applying ample heat at each step in the assembly of the lander to remove the maximum possible amount of contamination at that point in the process. This alternative has the advantage of increased assurance in meeting quarantine requirements. However, it would require the imposition of sterilization requirements on lower tier contractors and result in a large degree of redundance as "over-kill".

A number of alternate mixes of heating times can obviously be postulated in terms of their distribution between piece-part, flight acceptance and terminal sterilization times. The analysis reported in this section relates to the quantitative evaluation of such distributions and addresses itself to the following particular questions:

a. If it is desired to minimize terminal sterilization times, what are the relative magnitudes of flight acceptance and terminal sterilization times when the minimum terminal time is attained; and, is there a penalty in the total heat which the equipment would be subjected to while achieving minimum time during terminal sterilization?

b. Will there be a significant increase in heating times when the additional constraint is imposed that during the terminal cycle there is no requirement for the heat to reach buried contamination?

c. What are the merits of separately incorporating a heat cycle on the piece-part level in addition to heating these piece-parts at the flight acceptance and terminal sterilization cycles?

B. Method of Analysis

To avoid the analytical complexities which would result from a "three dimensional" problem wherein sterilization times are distributed between terminal, flight acceptance and piece-part heating, the approach

taken in the analysis was to first restrict the distribution of heat only to a terminal cycle and the flight acceptance of subassemblies, i.e. assuming that piece-parts are not subjected to heat. Results obtained in this manner are then extended to the case where piece-part heating is included. A computerized version of the generalized systems model, (Appendix B), was used to analyze this distribution of flight acceptance and terminal heating times.

For present purposes, the lander was conceptually portioned into four source classes, viz, exterior surfaces, interior surfaces, mated surfaces and buried (embedded) sources of contamination. A given location on the lander is so classified on the basis of its character in the finally assembled craft. For example, a location which during flight acceptance testing is an open surface but which is mated to another surface prior to terminal sterilization is classified as a mated surface. In this sense, the individual source classes assumed in the present analysis are, in reality, composite source classes. For this reason, recontamination of the mated source class is allowed for, so as to account for those mated surfaces which, during the flight acceptance cycle, were open surfaces.

It is also recognized that, operationally, there can be two types of buried sources of contamination, viz, those sources which are present prior to the flight acceptance cycle and those introduced after flight acceptance, i.e. in the course of final assembly. Therefore, the assumption of a single buried source class (without recontamination after the flight acceptance cycle) is tantamount to assuming that no buried sources of contamination are introduced after the flight acceptance cycle. This point must be kept in mind when interpreting the results of the present analysis because, to the extent that this assumption is not valid in actuality, the heating times reported herein would not be applicable.

It was assumed in this analysis that all of the (four) source classes are subjected to identical (constant temperature) heating times during the flight acceptance cycle. However, with regard to terminal heating, two separate cases were considered. In the first case, it is assumed that all four source classes are subjected to identical heating times. In the

second case it is assumed that exterior surfaces, interior open surfaces, and mated surfaces are subjected to identical heating times but that buried contamination receives no terminal heating whatsoever. The latter case was examined because of its considerable operational significance since it allows for what might be termed "surface sterilization" in the terminal cycle, i.e. there would be no requirement to reach lethal temperatures in the interior of materials thereby circumventing problems which stem from thermal inertias and their related thermal lags.

The final simplifying assumption made for the present analysis was that only two impact velocities are possible, viz (1) a soft landing wherein no fracture or breakup occurs and (2) a hard landing associated with a single velocity which exceeds the critical velocities of the various source classes.

C. Analytical Model

On the basis of the generalized model described in Chapter II (expressions 6 through 17) and the preceding assumptions and conventions, the average, or mean, number of organisms released onto the planet is expressible in the following form:

$$
\begin{aligned}
m(r) = & \left[m^{sx}(0)\ 10^{-\frac{t_{f/a}}{D_{sx}}} + \Delta m^{sx} \right] 10^{-t_s/D_{sx}} \\
& + P(V_H) \left\{ \left[m^{s}(0)\ 10^{-\frac{t_{f/a}}{D_{s}}} + \Delta m^{s} \right] 10^{-t_s/D_{s}} \right. \\
& + \left[m^{M}(0)\ 10^{-\frac{t_{f/a}}{D_{M}}} + \Delta m^{M} \right] 10^{-ts/D_{M}} \\
& \left. + m^{B}(0)\ 10^{-\frac{t_{f/a} + \delta ts}{D_{B}}} \right\} P(r/V_H)
\end{aligned}
$$

where

$m^{sx}(0)$, $m^{s}(0)$, $m^{M}(0)$, $m^{B}(0)$ = average bio-load (exterior, interior open, mated and buried, respectively) subjected to flight acceptance heating

Δm^{sx}, Δm^{s}, Δm^{M} = average recontamination loads (exterior, interior open, mated, respectively) between flight acceptance and terminal heating

D_{sx}, D_s, D_M, D_F = 125°C resistance values for exterior, interior open, mated and buried contamination sources, respectively

$P(V_H)$ = probability of a hard landing

$t_{f/a}$ = flight acceptance heating time (constant temperature equivalent)

t_s = terminal heating time (constant temperature equivalent

$$\delta = \begin{cases} 1 & , \text{ if buried contamination "sees" terminal heating} \\ 0 & , \text{ otherwise} \end{cases}$$

This reduced form of the generalized model, along with appropriate values for the various parameters, was used to evaluate the distribution of flight acceptance and terminal heating times which meet the implementation requirement m(r).

D. Parameter Values

Table III-1 defines the magnitudes of parameter values used in the analysis. As shown in the table, this is done in two categories. The first group of parameters, shown in the upper part of the table, have been assigned fixed values in all of the runs. The second group was assigned limiting values, to represent the range which these parameters are likely to assume. The basis for placing a parameter in one or the other of the above two categories has been the relative uncertainty of its numerical magnitude.

The value of m(r) is based upon a probability of growth, $p(g)=10^{-3}$ and an allocation for landing vehicles $p(N)=10^{-6}$. The D values given in the table are those currently provided by the NASA Planetary Quarantine Office to the Viking Project for the development of sterilization requirements. As regards the probability of a hard landing, $P(V_H)$, this parameter could readily be given a range of values extending beyond 10^{-1}, to say, 10^{-3} or 10^{-4}. This was not done since there is considerably more uncertainty with other aspects of microbial release, contained in the term $P(r/V_H)$ - the probability

TABLE III-1 Parameter Values for Analysis of Heating Time Distributions

Fixed Parameters:

Implementation Requirement	$m(r) = 10^{-3}$	
Microbial Resistance on surfaces	$D_S = 0.5$ hrs.	(external and internal surfaces)
" " " Mated Surfaces	$D_M = 1.0$ hrs	
" " of Buried Contamination	$D_B = 5.0$ hrs	
Probability of Hard Landing	$P(V_H) = 0.1$	

	Limiting Parameter Values	
	Worst Case	Best Case
Initial microbial loads - $m(0)_S$, $m(0)_{SX}$, $m(0)_M$ $m(0)_B$	10^7	10^4
Recontamination after f/a cycle on open surfaces - Δm^S	10^6	10^2
Recontamination after f/a cycle on mated surfaces - Δm^M	10^5	10^2
Probability of release given a hard landing — $P(r/V_H)$	1	2×10^{-3}

of release given that hard landing has occurred. This latter parameter is included in the category for which a range of values has been used.

The meaning of the "worst" and "best" case parameter values given in Table III-1 for the various microbial loads and the conditional release probability $P(r/V_H)$ deserves some elaboration, particularly in view of the somewhat arbitrary way in which the numerical magnitudes are assigned to their limiting values.

Either for the "worst" or "best" case, a projection has been made into the future as to the values which might be achieved for a given parameter depending upon the amount of effort that is applied. But such an effort suggests a cost, whether of a monetary value or other types of cost, e.g. complexity in implementation, impact on equipment reliability, etc. As an illustration, consider the value of the conditional release probability, $P(r/V_H)$. If the "worst" case value of unity is assumed there would obviously be no need for any effort to defend the fact that this is, indeed, the "worst" case. Similarly, an initial microbial load of 10^7 might not require extensive decontamination procedures, or elaborate bio-assay to justify that the load is of the given order of magnitude. These types of benefits must, however, be weighed against a possible penalty in increased heating times, either in flight acceptance or terminal sterilization. The "best" case, on the other hand, implies a cost which might stem from more complex bio-assay, extensive decontamination or clean-room assembly procedures, or difficulty in defending a lower value for the conditional release probability. These costs then need to be weighed against potential benefits in reduced heating times.

In summary, the "best" and "worst" case conditions are meaningful only in the context of the present analysis in that they represent a qualitative "cost" or a "benefit" in the implementation of sterilization requirements to be compared against the quantitative cost/benefit of heating times in terminal and flight acceptance cycles.

The particular values which were chosen for the "worst" and "best" case conditions derive from a general knowledge of the current state-of-the-art

relative to these parameters. They were arrived at both from an assessment of published information and by discussion with knowledgeable people in this field.

E. Results

Four separate series of computer runs were made using the model defined by expressions 6 through 18 and the parameter values provided in Table III-1. The series were distinguishable as to (a) whether the "best" or "worst" case parameter values were assumed and (b) whether buried contamination was or was not subjected to heat in the terminal cycle. Computation within a given series consisted of determining the minimum terminal heating time required in order to meet implementation requirements, for a specified (run dependent) value of the flight acceptance heating time. Figures III-1 through III-4 indicate the terminal and total (terminal plus flight acceptance) heating times plotted against flight acceptance heating time for each of the four situations considered.

For the situations wherein buried contamination is not subjected to terminal heating, minimum flight acceptance heating times are required in order to meet implementation requirements. This follows from the fact that below a certain level of flight acceptance heating the surviving buried load is unacceptably large, because it is not subjected to terminal heating.

To make a meaningful comparison of the four runs summarized in Figures III-1 through III-4 it is useful to focus on that value of $t_{f/a}$ at which the terminal sterilization time, t_s, is at a minimum, for, clearly, at larger values of $t_{f/a}$ the total time would increase without any benefit either in terminal time or in total time. These data points are summarized in Table III-2, showing the terminal and flight acceptance heating times for the "best" and the "worst" cases and distinguishing between the two conditions where buried contamination either is or is not subjected to lethal heat during the terminal cycle.

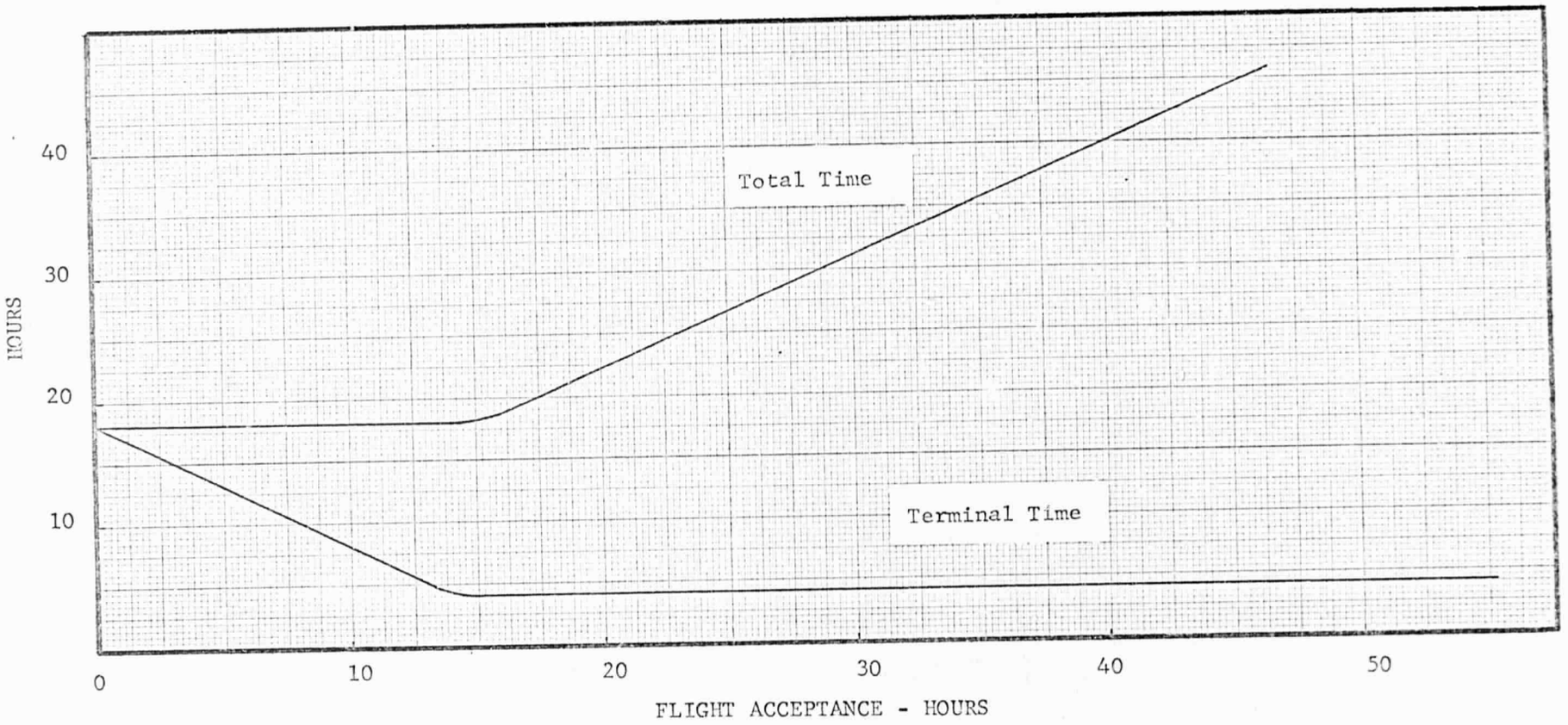


Fig. III- 1 Distribution of heating times for "best" case parameter values-buried contamination receives terminal heat cycle.

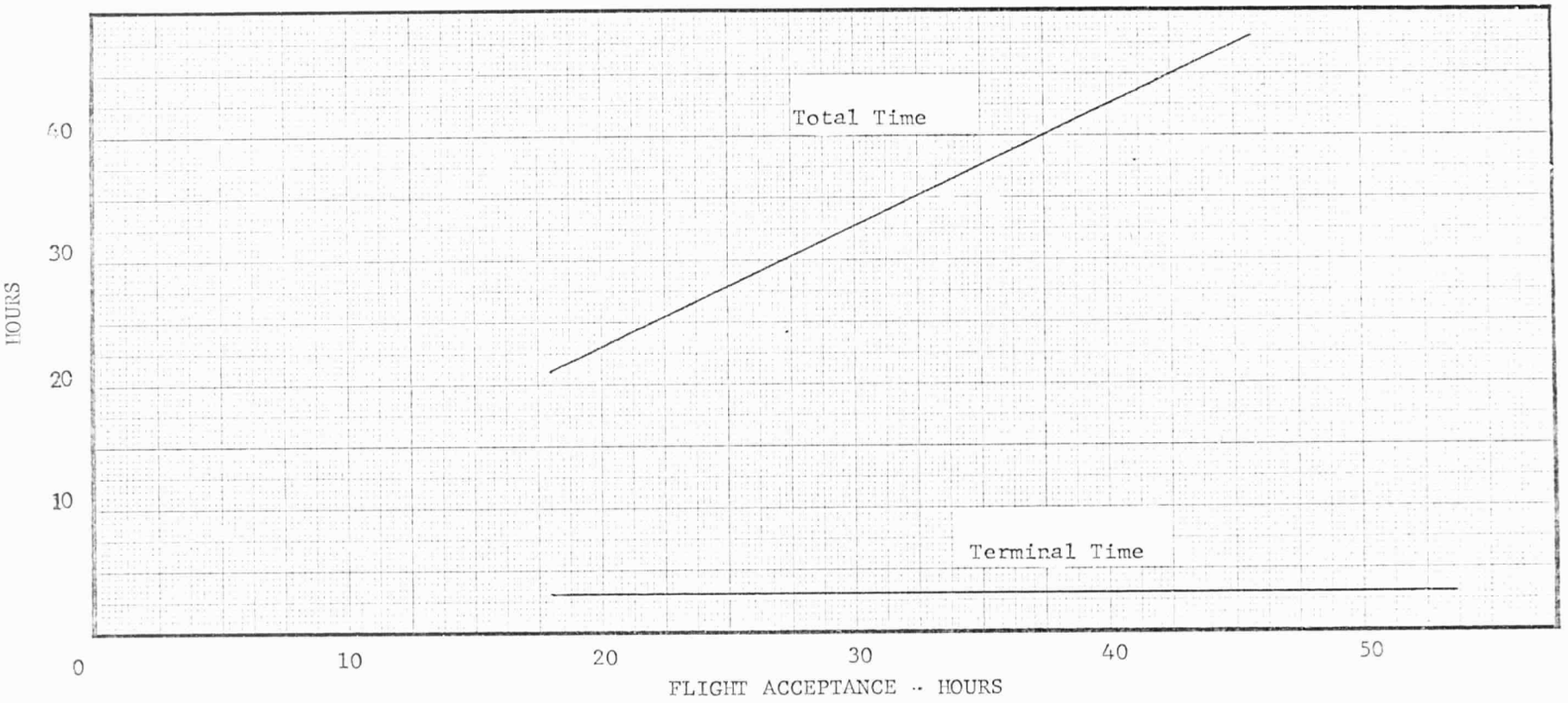


Fig. III-2 Distribution of heating times for "best" case parameter values-buried contamination not subjected to terminal heat cycle

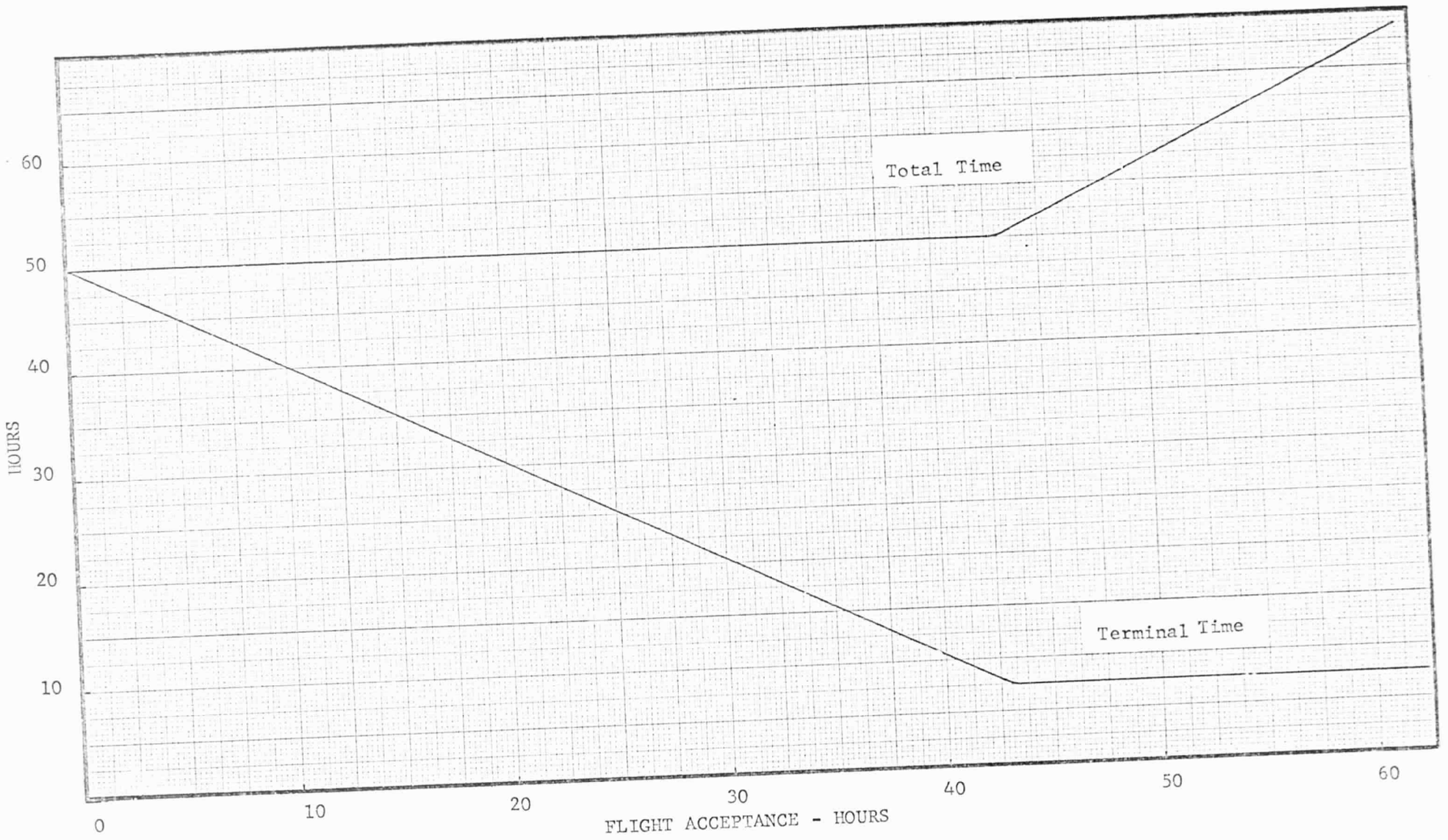


Fig. III -3 Distribution of heating times for "worst" case parameter values-buried contamination receives terminal heat cycle.

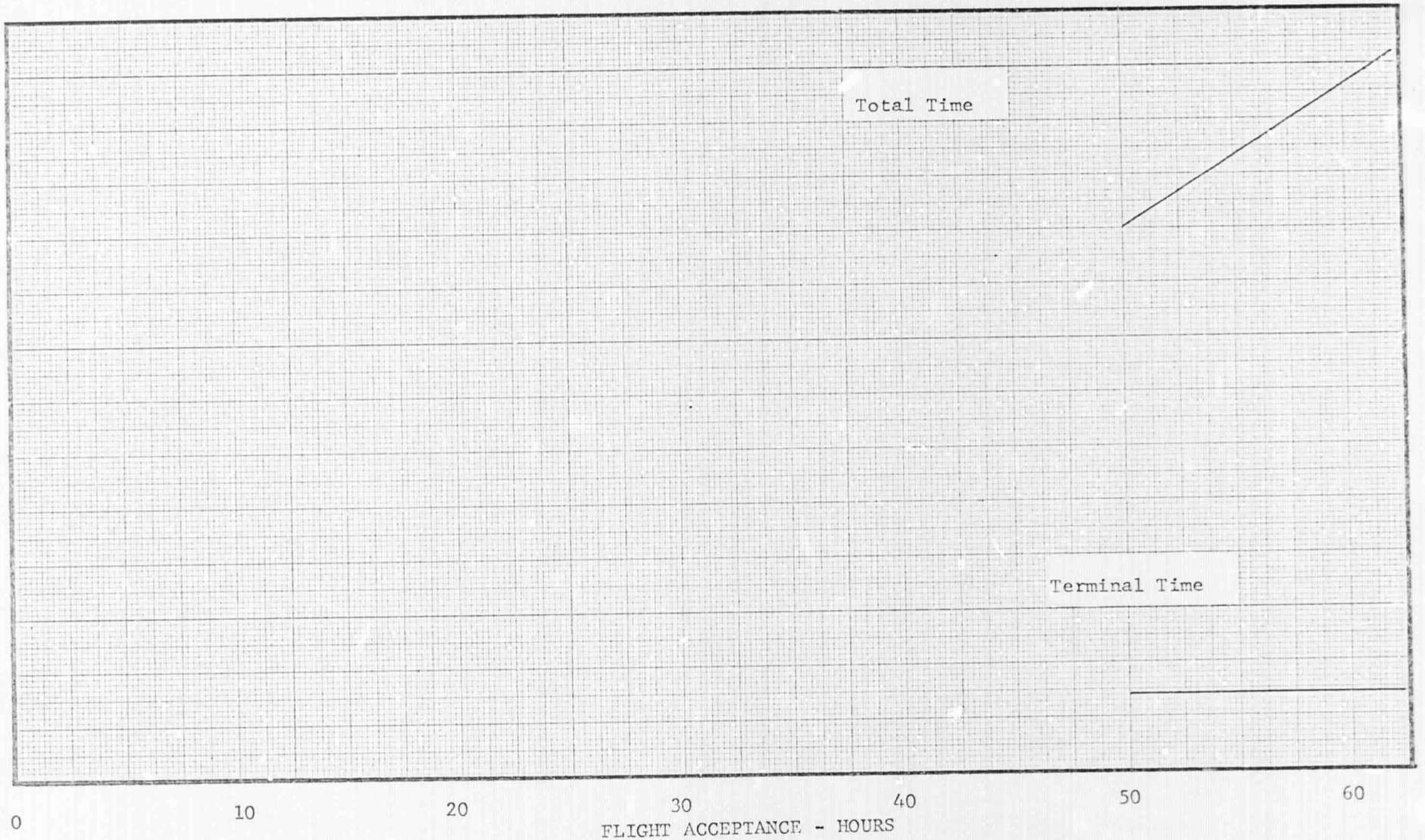


Fig: III-4 Distribution of heating times for "worst" case parameter values-buried contamination not subjected to terminal heat cycle

	Buried Contamination Exposed to Heat in Terminal Cycle		Only Surface Contaminants Heated in Terminal Cycle (No Heat Penetration)	
	t_s hrs	$t_{f/a}$ hrs	t_s hrs	$t_{f/a}$ hrs
Best Case	3	15	3	18
Worst Case	7	43	7	50

TABLE III-2: Comparative Heating Times

A number of observations may be pertinent with reference to the data shown in Table III-2:

a. As long as the requirement is imposed that sterilizing heat must reach the interior of all materials during terminal sterilization, there is a flexibility for distributing a required total amount of heat between flight acceptance and terminal cycles. The data in Table III-2 shows the limiting case where the terminal time has been minimized at the expense of increased flight acceptance time. However, the sum of these two values could be distributed in any other desired combination so long as the sum of the two remains the same.

b. Referring to the data applicable to the case where there is no heat penetration requirement in the terminal cycle, any redistribution between terminal and flight acceptance time must be at a penalty to the total time which the equipment will see.

c. The numerical data in Table III-2 provides an indication of the extent to which uncertainties of the parameter values will influence the length of heating times. For example, the terminal sterilization time could vary by a factor of about 2, whereas the corresponding flight acceptance times would be affected by about a factor of 3.

d. Terminal heating times are affected by the fact that heat penetration is not required in the terminal cycle, regardless of whether the "best" or "worst" case parameters are assumed. The penalty in this approach is in the flight acceptance heating times, but the magnitude of this penalty is not very significant. For example, in the "best" case situation the flight acceptance time increases to 18 hours from 15 hours and in the "worst" case it increases to 50 hours from 43 hours. But these increases must be weighed against the

considerable benefit which accrues from the fact that heat is not required to penetrate into those portions of the spacecraft which have substantial thermal inertia and thereby cause other parts of the spacecraft to acquire more total lethalty than is necessary.

The preceding analysis dealt exclusively with the distribution of heating times between the terminal and flight acceptance cycles. The question of further distributing the required heat to the piece-parts level can now be considered on the basis of the above results. The procedure is almost analogous to that used above in that one might consider the heat distribution between flight acceptance and piece-part heating on the assumption that the total amount of heat required is that derived above for the flight acceptance cycle. The model for such an analysis would again require an identification of an initial buried load contained within piece-parts, and subsequent recontamination in the process of assembly. This latter source is a much more likely possibility at the sub-assembly level in that such assembly processes frequently involve the use of encapsulating materials. It is evident, however, that when such an analysis is done on a quantitative basis, it will lead to the conclusions reached for the distribution of heat between terminal and flight acceptance times. It is, therefore, concluded that piece-part heating would be desirable only on a selective basis when the following conditions exist, either separately or in combination:

a. A piece-part is known to contain a relatively high initial buried load and it is desired to reduce this load so as not to penalize other parts in the assembly which would not require a comparable amount of heat.

b. A piece-part is known to be marginal in terms of its ability to withstand prescribed heat levels and it is desired to establish its functional capabilities at an early enough stage in the assembly process so as to avoid the cost due to malfunction at a later stage.

c. A piece-part is known to have a high thermal inertia so as to cause difficulty in achieving uniform heating at the assembly level relative to other parts in the assembly.

d. In the event that a less conservative value of the conditional release probability is ultimately used, based upon a nominal fracture ratio for spacecraft materials, and a particular piece-part is known to be unusually fragile and, therefore, inconsistent with the chosen nominal fracture ratio, such a piece-part could be selectively subjected to a heat cycle to reduce its dominant contribution to the probability of survival of buried organisms in that piece.

IV. SENSITIVITY ANALYSIS

A. Objective

As indicated in the preceding section of this report, significant reductions in flight acceptance and total heating times can be obtained by demonstrating, or otherwise justifying, the best-case parameter values. However, before embarking on efforts to demonstrate or produce less conservative parameter values, it would be of interest to know the benefits, in terms of reduced heating times, resulting from less-than-worst-case values of these parameters. This section is, therefore, devoted to estimating and comparing reductions in terminal and flight acceptance heating times resulting from improvements in individual parameter values.

B. Method of Analysis

In principle, the benefits of reduced heating times resulting from an improvement in the value of any given parameter can be obtained from a knowledge of the relationship between the required flight acceptance and terminal heating times and the parameter itself. This relationship depends, however, upon the assumed values of the remaining parameters. To avoid these complex interrelationships, the approach adopted herein is to examine the reductions in "optimum" flight acceptance and terminal heating times separately resulting from improvements in particular parameter values. It will be recalled that optimum in this sense refers to the flight acceptance and terminal heating times when terminal heating is essentially minimized and flight acceptance heating is minimized for that minimum terminal time.

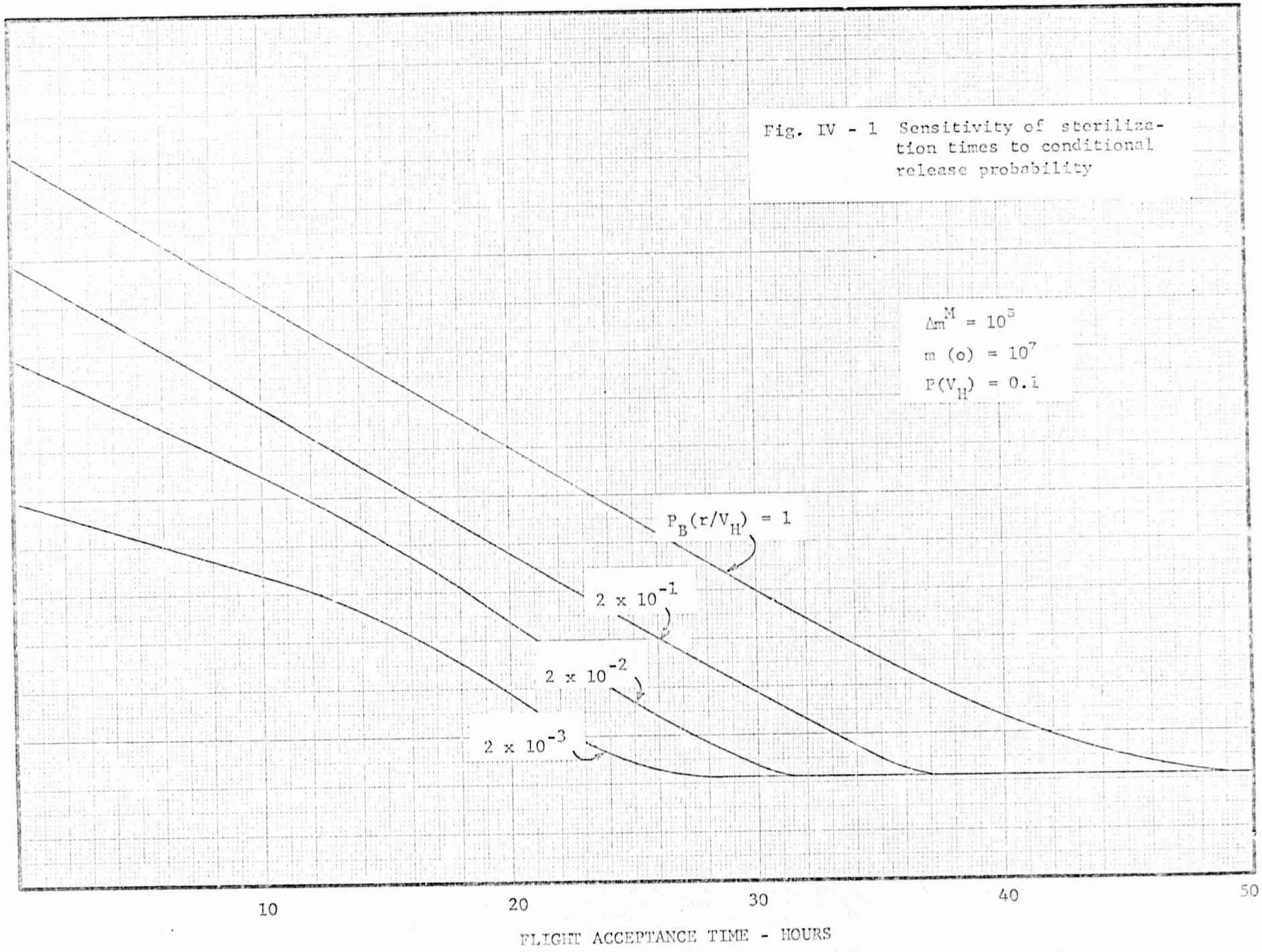
For present purposes it is assumed that reductions in heating times at the optimum values are relatively insensitive to whether the buried contamination is or is not subjected to terminal heating. This appears justified on the basis of the data contained in Table III-2 and Figures III-1 through III-4 of the preceding section. Thus, for the case where buried contamination <u>is</u> subjected to terminal heating times the difference between "worst" and "best" case heating times is 4 hours for t_s and 28 hours for $t_{f/a}$. In the case where buried contamination <u>is not</u> subjected to terminal heating

the corresponding differences are 4 and 32 hours for t_s and $t_{f/a}$ respectively. Variations of these magnitudes are not considered significant in the present sensitivity analysis as they will not influence the conclusions concerning the relative effect of parameter values on heating times. Therefore, the analysis presented in this section is based only on the case where the buried contamination receives terminal heating.

The parameters investigated consist of the constraint m(r), the initial mated and buried bio-loads, the recontamination of mated surfaces, the probability of a hard landing and the probability of release of buried contamination, conditional upon hard landing. The analysis of the preceding section does not justify further consideration of exterior and interior open surface contamination, owing to the relatively small D-value associated with these contamination sources.

The approach adopted for measuring the sensitivity of heating times to the individual parameter values can be illustrated in terms of the probability of release of buried contamination. Figure IV-1 indicates the dependence of the required terminal time associated with prescribed flight acceptance heating times. As indicated, the individual curves are distinguished by the assumed value of the release probability $P_B(r/V_H)$ which, in this case, is allowed to take intermediate values between the worst and best case values, (i.e., $P(r) = 1$, 2×10^{-2}, and 2×10^{-3}). Worst case values of all other parameters, as defined in Table III-1 of the preceding section, were used in developing these curves. Accepting the criterion that $t_{f/a}$ be selected to be the minimum value which "essentially" minimizes the terminal heating time. The following approximate dependence of $t_{f/a}$ and t_s upon $P_B(r/V_H)$ results:

$P_B(r/V_H)$	$t_{f/a}$	t_s
1	49	7
2×10^{-1}	37	7
2×10^{-2}	31	7
2×10^{-4}	27	7


Fig. IV - 1 Sensitivity of sterilization times to conditional release probability
$\Delta m^M = 10^5$
$m(o) = 10^7$
$P(V_H) = 0.1$
$P_B(r/V_H) = 1$
2×10^{-1}
2×10^{-2}
2×10^{-3}
TERMINAL TIME - HOURS
FLIGHT ACCEPTANCE TIME - HOURS
0
10
20
30
40
50

The values for $t_{f/a}$ in this table were read from the individual curves as those values where the terminal heating times effectively settle down to a constant value, i.e., any increase in $t_{f/a}$ buys very little, if any, reduction in terminal heating time and any decrease in $t_{f/a}$ tends to increase the total heating time. These particular results indicate that a one order of magnitude decrease in $P_B(r/V_H)$ produces a 25 percent decrease in f/a heating time whereas each successive order of magnitude decrease in $P_B(r/V_H)$ results in substantially less reduction in $t_{f/a}$. However, improvements in $P_B(r/V_H)$ result in essentially no reduction in the terminal heating time.

C. Results

The approach described above for evaluating the effect of the conditional probability of release was also applied to all the other parameters considered in this section. Figures IV-1 through IV-5 provide the data on terminal time variation versus f/a time for each of the parameters, considering both the worst and best cases for the parameter studied. These curves were then used to produce the summary data shown in Table IV-1.

Referring to Table IV-1, the previously used best and worst case heating times are noted in this table for reference purposes. To illustrate the use of this table, consider again the parameter $P_B(r/V_H)$ for the probability of release given hard impact. If this parameter could be demonstrated to assume the best value of 2.1×10^{-3} then the corresponding change in terminal sterilization time would be as given in the table, i.e., it would remain at 7.1 hours with 0 percent improvement since it corresponds to the worst case for all parameters. However, the flight acceptance cycle heating time would change from the worst case value of 49 hours to 21 hours, producing a 57 percent reduction in flight acceptance time due entirely to the change in the value of the probability of release. The fact that this probability of release has no effect on terminal sterilization time is readily explained since it is associated entirely with buried contamination which is reduced, almost exclusively, in the flight acceptance cycle.

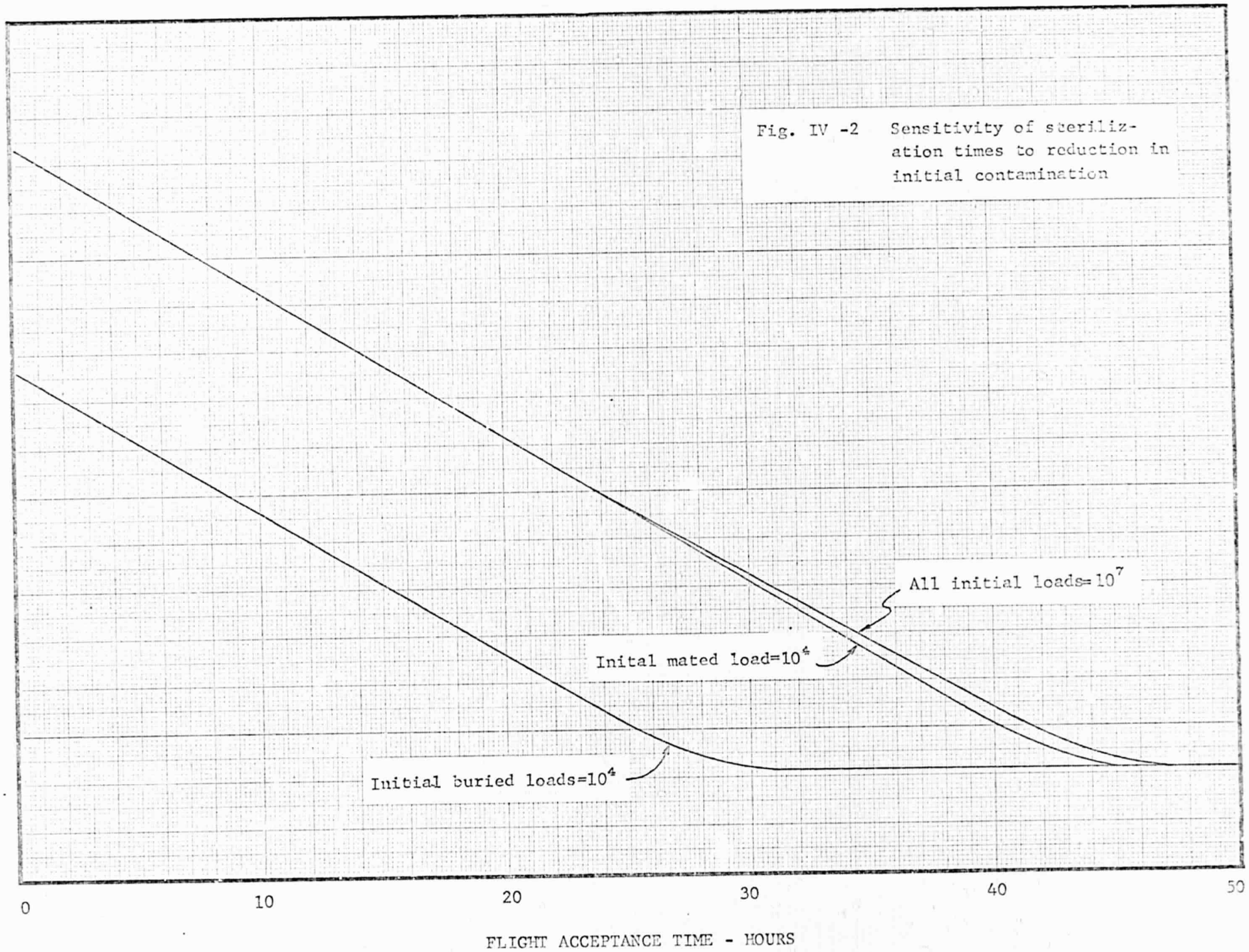


Fig. IV -2 Sensitivity of sterilization times to reduction in initial contamination

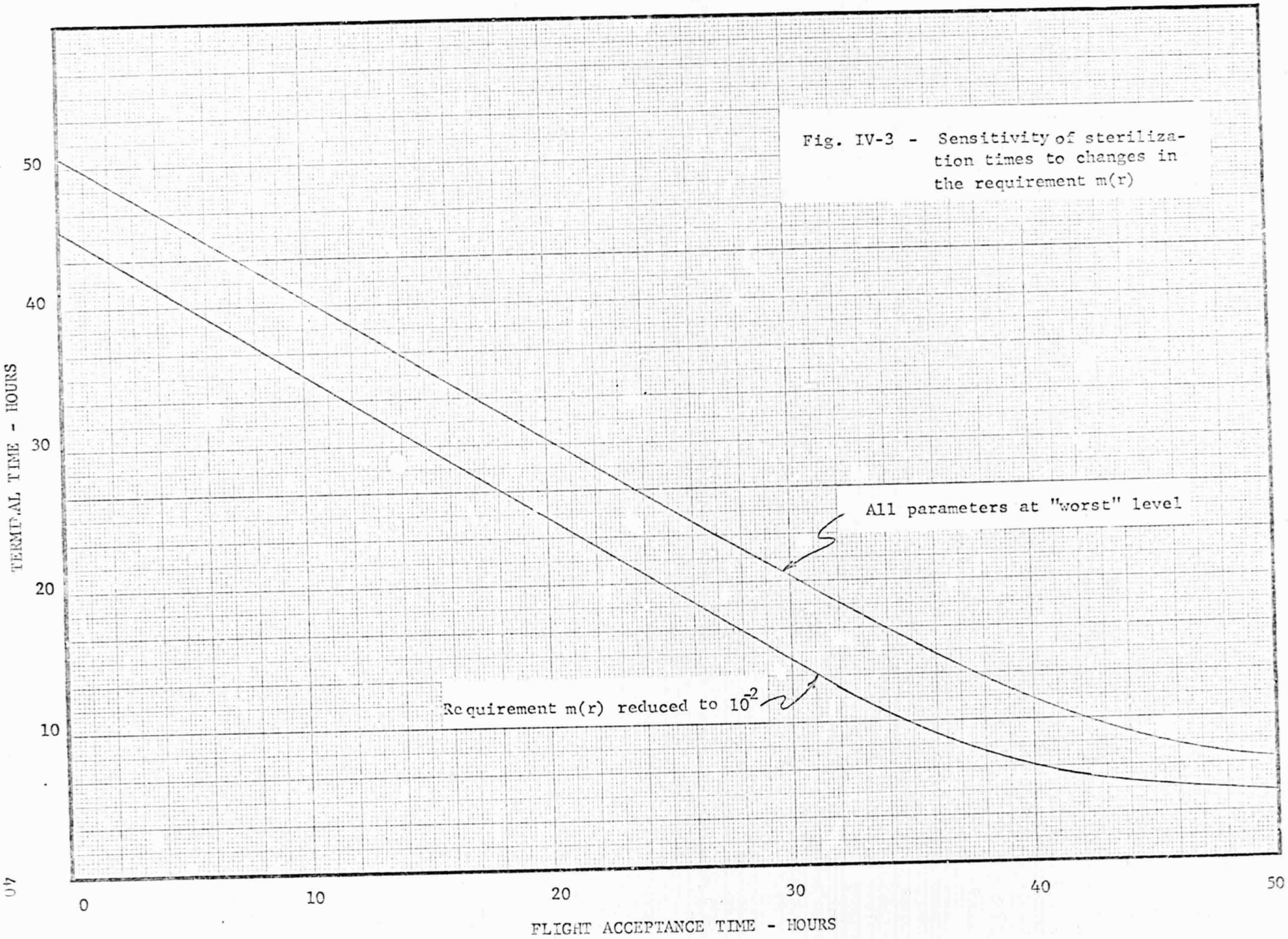


Fig. IV-3 - Sensitivity of sterilization times to changes in the requirement m(r)

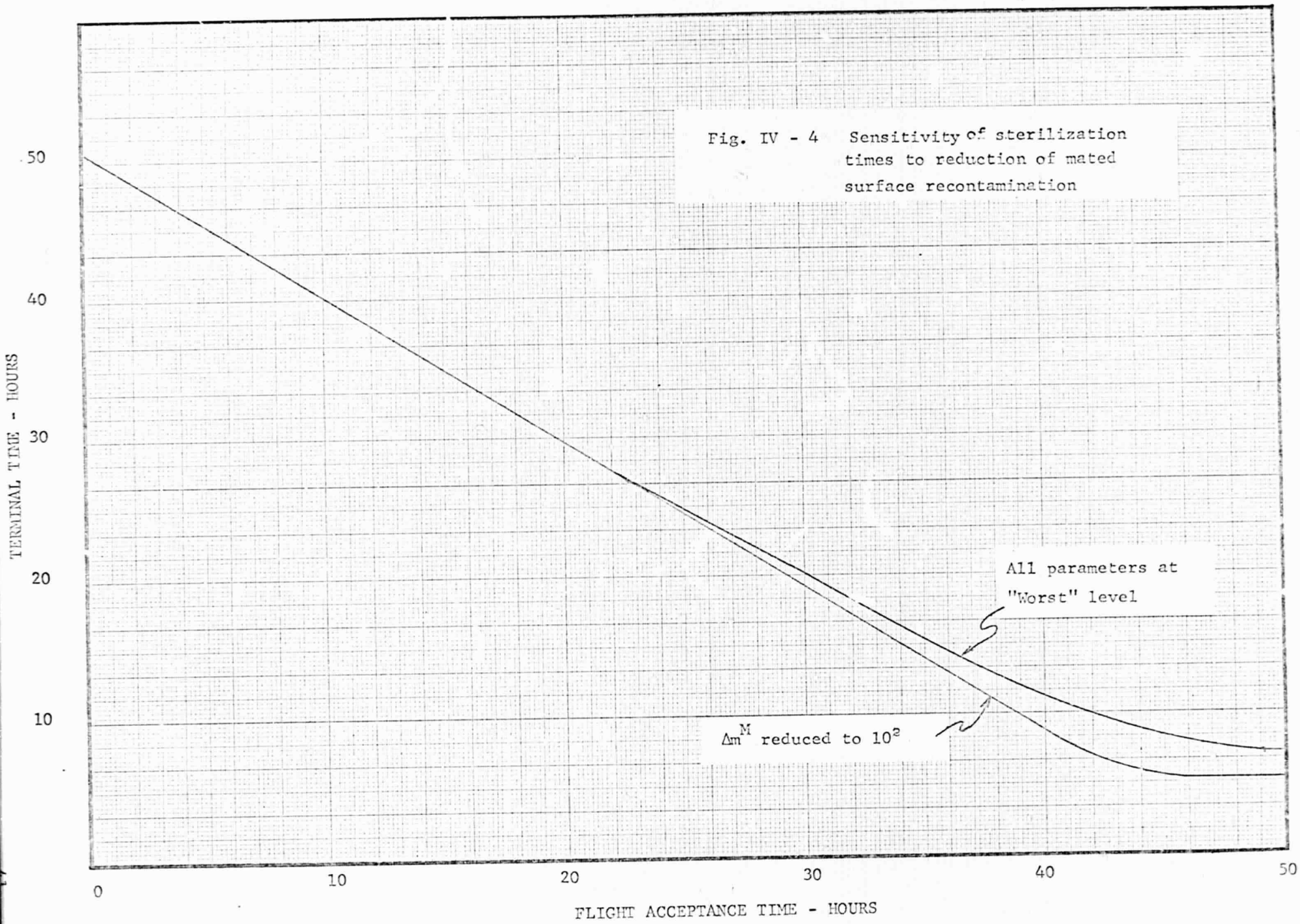


Fig. IV - 4 Sensitivity of sterilization times to reduction of mated surface recontamination

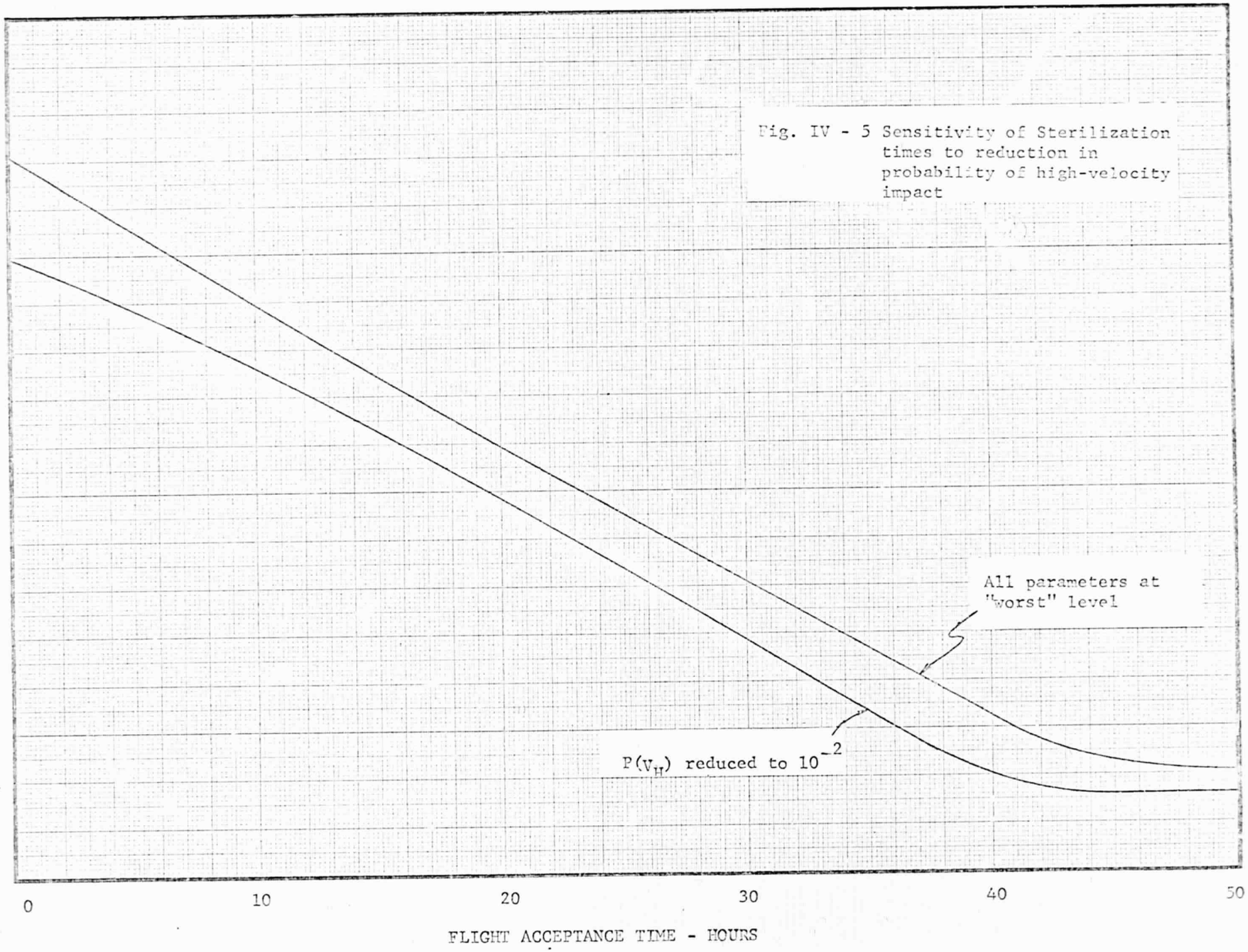


Fig. IV - 5 Sensitivity of Sterilization times to reduction in probability of high-velocity impact

Reference heating times: worst case $t_s = 7.1$ $t_{f/a} = 49$ best case $t_s = 2.1$ $t_{f/a} = 10.5$						
PARAMETER			Improvement in t_s		Improvement in $t_{f/a}$	
Description	Worst Value	Best Value	t_s - hrs	% improvement	$t_{f/a}$ - hrs.	% improvement
$P_B(r/V_H)$	1	2.1×10^{-3}	7.1	0	28	43
$P(V_H)$	.1	10^{-3}	5.3	25	44	10
$M(^0)_B$	10^7	10^4	7.1	0	30	40
Δm_M	10^5	10^2	5.3	25	45	8
R	10^{-3}	10^{-2}	5	30	47	4

TABLE IV-1

Sensitivity of Heating Times to Parameter Values

An effect similar to that of probability of release, and for similar reasons, is noted for the initial buried load $n_B^{(o)}$. Again, the terminal sterilization time is not influenced by a reduction of the buried load from its worst case value of 10^7 to the best case value of 10^4. However, flight acceptance time would be reduced from the worst case condition of 49 hours to about 30 hours through minimization of the initial buried load. (Referring to Figure IV-2, an analysis was also made of the effect of the initial mated load, i.e., the load which is present in the mated surfaces of spacecraft sub-assemblies. It is evident from this graph that this initial mated load has no significant influence either on terminal or flight acceptance heating times.)

Table IV-1 shows that the terminal sterilization time could be influenced through the parameters $P(V_H)$--the probability of hard impact, Δm_M -- the recontamination occurring on mated surfaces following flight acceptance and the requirement R (which reflects either the allocation given to landing vehicles or the value of probability of growth on the planet). These three parameters individually produce a reduction of approximately two hours, or 30 percent each, in the terminal sterilization time. They also influence the flight acceptance time but to a lesser degree than the probability of release $P_B(r/V_H)$ or the initial buried load.

The effect of $P(V_H)$ and m on terminal sterilization times is readily explained by the fact that these parameters deal largely with post flight acceptance events. To the extent that these parameters also influence pre-flight acceptance requirements, they produce a small but noticeable effect on flight acceptance heating times.

In utilizing the data provided in Table IV-1, it must be recognized that the reductions in heating times relate to the effect of each parameter taken one at a time. Thus, if all the parameters are improved to their best values the best case heating times would of course result, as shown in the preceding section. However, taking any combination of improved parameter values will yield an improvement in the heating times approximately, but not exactly, in accordance with the sum of the percentages indicated in the table.

The sensitivity data provided herein shows the quantifiable benefits resulting from parameter value improvements in terms of heating times. The decision to embark upon programs which will produce these values depends, however, on additional and, in part, unquantifiable considerations. Although no attempt is made here to develop and justify an optimum program which will, from a cost benefit point of view, minimize equipment heating times, a few considerations are worth noting. For example, those concerned with project implementation of a landing mission may wish to consider methods for either controlling or accurately estimating contamination loads for buried contamination and recontamination of mated surfaces during final assembly. These parameters alone can produce a significant change both in terminal heating as well as flight acceptance heating times. Furthermore, project personnel also have an influence over the estimation and possibly control of the probability of a hard landing, since this parameter is closely related to equipment reliability. This factor can also influence terminal flight acceptance heating times. On the other hand, parameters dealing with the imposed requirements, R, or the probability of release given a hard landing, $P_B(r/V_H)$, are subject to different types of judgment. These latter factors can also contribute significantly to reduction of terminal and flight acceptance heating times and the section which follows treats the estimation of $P_B(r/V_H)$ in greater detail.

V. ESTIMATION OF MICROBIAL RELEASE PROBABILITIES

A. Objective

In the preceding sensitivity analysis two parameters were considered relating to the release of micro-organisms from the spacecraft onto the planet surface. They were, respectively $P(V_H)$, the probability of a high velocity impact, and $P_B(r/V_H)$, the probability of release given that a high velocity impact has occurred. Both of these parameters were found to significantly influence sterilization times in terminal as well as flight acceptance cycles. However, different considerations enter into the process of reducing these parameters to the preferred values which yield benefits in sterilization heating times.

A high velocity impact is, as previously defined, one which is greater than the velocity for which a lander has been designed. Such an anomalous impact velocity can occur from any combination of: (1) excessive trajectory entry angle, allowing insufficient retardation by aerodynamic drag; (2) unaccounted-for atmospheric conditions, e.g. density or composition; and, (3) malfunctions in the decent/retardation system. The magnitude of the anomalous impact velocity will vary (see discussion in reference 1) according to the combination of events which produce it. Similarly, the probability of its occurrence will depend, in part, upon the magnitude of the velocity considered. It is evident, therefore, that an analysis of the probability of high velocity impact must concern itself with detailed mission and space vehicle design characteristics. The cost benefit considerations are, in this case, entirely mission specific and must be evaluated by project personnel in terms of (1) the benefit of reduced heating times which result from smaller values for the probability of accidental impact and (2) the difficulty of estimating and defending probabilities of high velocity impact substantially smaller than 0.1. Further analysis of $P(V_H)$ in the context of this study is, therefore, not useful.

An entirely different situation exists with respect to the probability of release given that a high velocity impact has occurred, $P_B(r/V_H)$. Currently this conditional release probability is associated with two dominant physical mechanisms. One of these deals with the breakup of spacecraft materials upon impact and the resultant release of micro-organisms from fractured surfaces. The second mechanism is that of erosion of spacecraft surfaces, including the surfaces of fractured pieces. These two processes contain a number of parameters upon which the estimation of the probability of release depends. Thus, in order to assess the realizability of lower conditional release probability values, it is necessary to investigate the various parameters involved in the formulation of release mechanisms. The principal purpose of the application study summarized herein has been to make such an estimate in order to provide a basis for assessing the difficulty and the specific steps involved in deriving and defending lower conditional release probability values. This could then be weighed against the benefits in reduced heating times which will accrue from such lower values.

B. Method of Analysis

The analytical framework used in the analysis is of limited scope in that it encompasses, at this point, only the major factors which enter into fracture and erosion mechanisms and their interdependencies. The simplifications utilized in order to derive a workable analytical basis included the following:

A. The generalized equation for the probability of release as given in intergal form in equation (14) was reduced to the consideration of a single velocity only.

B. As previously described, the probability of microbial release from open surfaces has been taken as unity, the probability of release from mated surfaces was taken to be equal only to the probability of high velocity impact, i.e. the probability of release given impact is taken as unity. The only remaining factor is, therefore, the probability of release, given impact, for buried contamination.

The analytical formulation of probability of release given impact for buried contamination which results from the above simplifying assumptions is summarized below.

$$P_B(r/V_I) = g_k(V_I)\left[P_k(r_I/V_I) + \left\{1 - P_k(r_I/V_I)\right\} q_k(s/e)\ P_k(r_e/V_I)\right]$$

$$\text{for } V_I \geq V_k^c \qquad (1)$$

where $P_k(r_I/V_I)$ is defined as the probability of release due to impact at impact velocity V_I, and is given by

$$P_k(r_I/V_I) = \begin{cases} \lambda f_k(V_I) & V_I \geq V_k^c \\ 0 & \text{otherwise} \end{cases} \qquad (2)$$

and $P_k(r_e/V_I)$ is given by

$$P_k(r_e/V_I) = \begin{cases} e_k t_q \left[f^{(o)} + f^{(1)}(V_I) + f_k(V_I)\right] & V_I \geq V_k^c \\ e_k t_q f^{(o)} & \text{otherwise} \end{cases} \qquad (3)$$

The definitions of parameters used above are as follows:

- λ - effective depth of exposure
- e - rate of erosion (assumed to be constant)
- t_I - quarantine time
- $f^{(o)}$ - ratio of area exposed to initial volume assuming no break up
- $f^{(1)}$ - ratio of additional area exposed as a result of the source breaking away from the craft to initial volume
- $f_k(V_I)$ - fracture ratio associated with the kth source at a given impact velocity
- $g_k(V_I)$ - conditional probability that a randomly selected organism from the kth (buried) source class survives impact, given impact velocity V_I.
- $q_k(s/e)$ - conditional probability that a randomly selected organism from the kth source class and which survives impact, survives erosion mechanism at a particular rate of erosion.

Even the above simplified formulation contains too many individual parameters to be amenable to quantitative analysis in the light of the very limited state of knowledge about the mechanisms involved and the parameters associated with them. Further quantitative simplifications are therefore necessary at this point. Some of these are readily made without penalty in the study. For example, a fixed value for the period of quarantine, t_q, can realisticly be assumed and the value of 17 years was used in the analysis. Furthermore, the relative magnitudes of $f^{(o)}$ and $f^{(1)}$, compared to $f_k(V_I)$ are such that the first two can be assigned fixed values based upon an estimate of surface area to total volume of a typical spacecraft in an intact conditon. However, the fracture ratio $f_k(V_I)$ was allowed to vary up to a magnitude of 10^6 1/m for the reasons described below.

Since the estimation of fracture ratios for different spacecraft materials and over a range of impact velocities is a complex task, it is useful to obtain some appreciation for the physical significance of the numerical magnitudes involved. It is particularly relevant to bound the magnitude of the fracture ratio in the context of microbial release. For these purposes, consider a cube of solid material measuring one foot (0.3 meters) on each side. Assume, next, that this cube is successively partitioned (fractured) into smaller sub-cubes of equal size. Table V-I indicates the fracture ratios (newly exposed areas divided by the original volume of one cubic foot), the resulting number of fractured sub-cubes and the corresponding dimension of the sub-cube. Thus, a fracture ratio of 10^3 (in units of 1/m) implies a break-up of the original cube into 150,000 pieces (sub-cubes). More significantly, however, a fracture ratio of 6×10^6 implies complete pulverization into one micron pieces. Since the size of micro-organisms is about one micron, a fracture ratio of about 10^6 is the upper bound which could reasonably be considered for our purposes, i.e. ignoring "breakage" of micro-organisms, it is the limiting value at which <u>all</u> organisms present would be released from the surrounding material.

Table V-I

Illustrative Fracture Ratios for a One Foot Cube

Fracture ratio - 1/m	No. of fractured cubes	Sub-Cube Dimension
10^1	4	200 mm
10^2	200	50
10^3	1.5×10^5	6
10^4	1.2×10^8	620 μ
10^5	1.2×10^{11}	62 μ
10^6	1.2×10^{14}	6.2 μ
6×10^6	$2.\_ \times 10^{16}$	1.0 μ

Determination of a numerical magnitude for the exposure depth coefficient, λ, can be approached from an intuitive as well as an experimental point of view. Intuitively, its numerical value would seem to be closely related to the physical dimension of a micro-organism. For, as noted earlier, this parameter effectively defines the depth below the exposed surface where a micro-organism, if present, would be considered to have been exposed in the sense that it would be capable of growth and spreading on the planet. Thus, assuming the average dimension of micro-organisms to be about 1 micron, letting $\lambda = 1\mu$ would imply that so long as any part of the organism is visible at the exposed surface, it is considered to have been released.

The value of λ was also derived experimentally (Peterson, et al 3) by the controlled fracture and culturing of sample materials into which a predetermined number of viable organisms was encapsulated. The value of λ derived in this manner was about 2.8 microns. To reconcile it with the intuitive value of $\lambda = 1$ micron, it could reasonably be argued that the experimental values reflect, in part, the depth of penetration of the nutrient medium below the exposed surface, and/or that the actual area exposed by fracture is not the smooth surface represented by the measurements. Such a reconciliation is, however, hardly worth the effort in view of the much greater uncertainties which are currently associated with other parameters in the model, in general, and with the release due to impact, in particular. A value of $\lambda = 1$ micron was, therefore, used in the quantitative exercise of the release model.

The parameter e, given as the rate of material erosion in meters per year, represents a crude model of the release of micro-organisms due to erosion: it simply assumes that as spacecraft surfaces are eroded due to their exposure to the planetary environment, small pieces of material are removed in layers and in this process, micro-organisms contained in the material are released. Although more detailed examination of erosion processes on planetary surfaces is currently in progress (ref. 2), analysis reported herein could not as yet benefit from more realistic representations. For this reason, the range of values assumed in the quantitative analysis for e is somewhat arbitrary and includes values from 10^{-4} meters per year to 10^{-6} meters per year. It remains to be established whether this is a representative range, but it appeared intuitively appropriate at the present time.

In view of the above uncertainties in quantitative values of material erosion parameters, it also did not seem reasonable to separately assign a range of values for the probability of microbial survival in the course of erosion. There is some indication from experimental work that a process which erodes hard materials at a high rate would involve energies also capable of rendering at least a portion of the microorganisms contained in the material non-viable. Thus, the probability q (s/e), representing the survival of microorganisms during erosion, is likely to be less than unity. However, for the purposes of the present preliminary analysis this probability was taken as unity. For similar reasons the probability of microbial survival in the course of fracture was also taken to be unity even though there is more concrete evidence from laboratory experimentation (ref. 10) indicating a definite destructive process in the course of fracturing at high velocities, apparently due to the heat generated in this process.

C. Results

The principal benefit from the analysis performed to date is the identification of areas of uncertainty, the clarification of which is likely to lead to reduced values of release probabilities. To illustrate this, reference is made to Figure V-1 in which the probability of release given high velocity impact, $P_B(r/N_H)$, is plotted against the fracture ratio, f , with the erosion rate e as a parameter. In terms of the limits used in the sensitivity analysis,

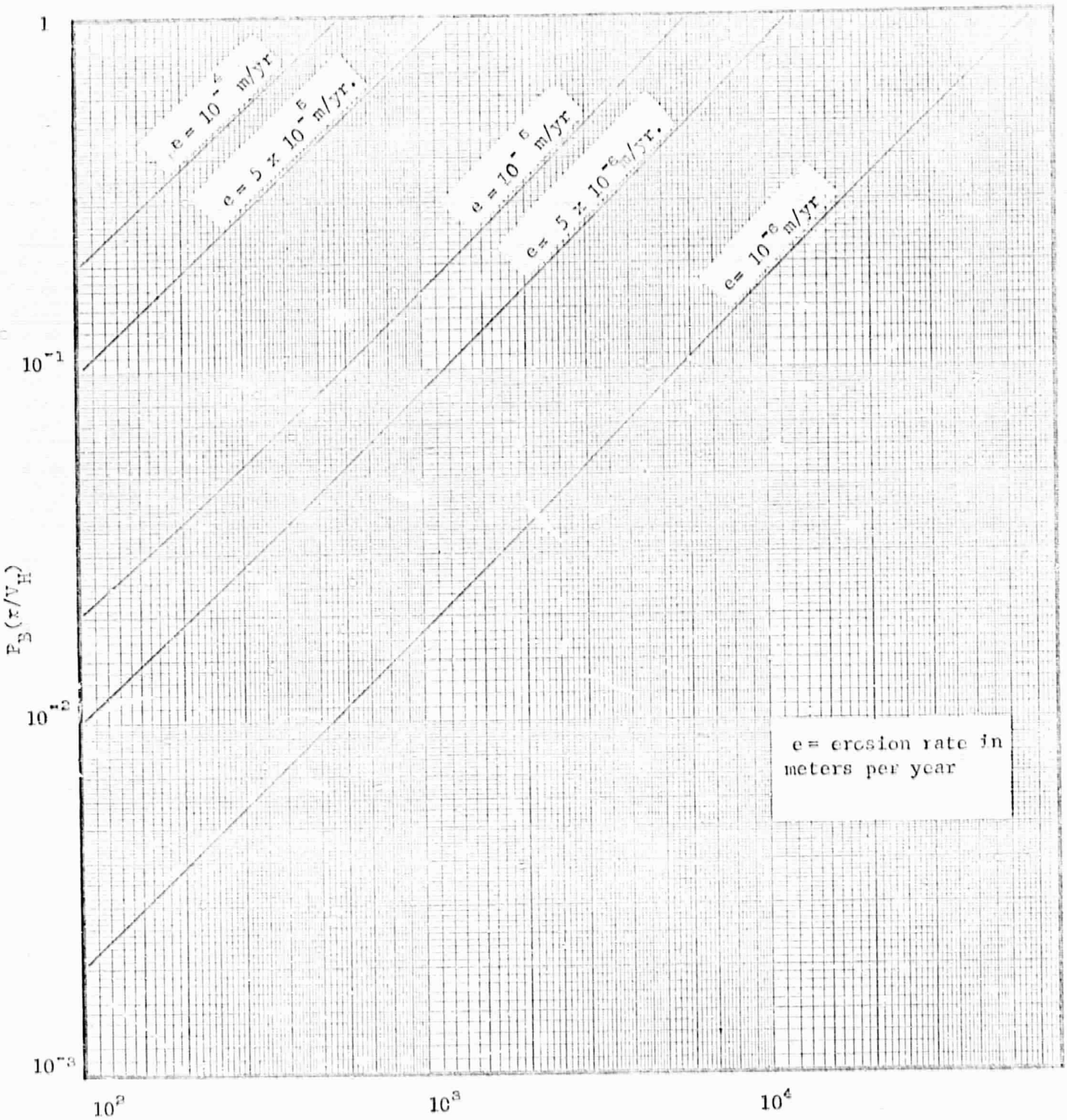


Fig. V - 1

Conditional release probability as a function of fracture-ratio and erosion rate

the desired lower value of $P_B(r/V_H)$ of about 2×10^{-3} would be realized if the fracture ratio could be demonstrated to be 10^2 while the erosion rate is taken at 10^{-6} m or 1 micron per year. These parameter values are about the lowest that could reasonably be considered at this time. However, as noted earlier, no allowance is made herein for microbial destruction both in the course of fracture as well as in the process of erosion. Their inclusion could make the target of $P_B(r/V_H)=10^{-3}$ an attainable one. However, considerably more work is required to formulate a defensible mechanism for the erosion process in terms of parameters of the anticipated environment on the planet surface as well as of the physical processes involved. Furthermore, the selection of a fracture ratio cannot be made independent of velocities of impact and the correlation between the chosen fracture ratio and the most probable impact velocity must also be identified. (For example, a distribution of velocities and the corresponding fracture ratios can be used to derive an expected fracture ratio, suitable for analysis purposes.)

Some of the recommended work described above is currently in progress both at Exotech and by other organizations with the support of the NASA Planetary Quarantine Office. The results which will be forthcoming should provide a better basis for estimating the probability of microbial release. The work reported herein provides a framework by which such results can be correlated to the development of heat sterilization requirements.

VI. CONCLUSIONS AND RECOMMENDATIONS

Analytical models and their applications serve a dual function in providing a basis for spacecraft sterilization. Furthermore, these two functions are overlapping and the process of analysis is an iterative one. Thus, at any point in time, a model can be formulated to define sterilization requirements based on current understanding and using existing data. Such a model can also be enlarged to include as yet unknown aspects, so as to evaluate the need for additional data and to order the priorities for further research and development. As new data becomes available, the models can also be enlarged to provide a better representation of the problem, and the process reiterated.

Efforts to date reflect a number of iterations in the above sense. Thus, it is a characteristic of early models and their applications that they were analytically simple but resulted in conservative requirements. It was also to be expected that, as the data base and understanding broadened, the models would become analytically more complex. The analytical model developed under this program was formulated in sufficient generality to suit projected future applications as well as application studies of current interest, e.g. those described herein.

Extension or modification of the model needs to be considered in the following areas:

(a) Estimation of microbial release probabilities, to better account for fracture and erosion processes while relating to parameters of the planetary environment (currently in progress at Exotech under Contract NASw-1734.

(b) Evaluation of alternate representations of microbial survival, in lieu of the exponential model, e.g. the stochastic diffusion model being developed by Exotech or the kinetic reaction-rate model being developed at Sandia. The benefits of such models from a systems point of view also deserve investigation.

(c) Inclusion of in-flight recontamination into the model.

(d) Extension of the model to provide an operational tool in making allocations to individual spacecraft sub-assemblies, in a manner analogous to that used in reliability analysis and control.

With regard to the implementation of sterilization requirements on a flight project, attention is invited to the following:

1. There is considerable merit to the approach wherein the contribution of buried loads to planetary contamination is essentially removed in the course of flight acceptance heating, provided no new buried contamination is produced thereafter. This approach allows the restriction of heat in the terminal cycle to open and mated surfaces which were contaminated after flight acceptance.

2. A desirable corollary to (1) above is the fact that terminal sterilization times are significantly smaller than flight acceptance heating times, without significant penalties in the total time which equipment would be subjected to heat (the ratio of $t_{f/a}$ to t_s is between about 5 and 7, depending upon whether the "best" or "worst" case parameter values are assumed).

3. The use of piece-part heating appears to be of merit only on a selective basis, depending upon whether the part is heat labile, has high thermal inertia, has excessive buried contamination or is unusally fragile.

4. Surface contamination is not a critical factor from the point-of-view of heat sterilization requirements. In this sense, it should not require high accuracy estimation or costly controls.

5. Mated contamination produced after flight-acceptance is a significant factor in determining the terminal heat cycle but it is not obvious whether the 2-3 hours which would be gained through control and accurate estimation of this contamination source would be consistent with the cost of achieving this benefit.

6. Buried contamination is a significant factor in determining the magnitude of the f/a cycle, and the development of better techniques for estimating this load should be given emphasis.

7. The demonstration of probabilities of high-velocity impact of less than 0.1 has a direct payoff in reduced heating times and therefore deserves consideration.

Some of the above considerations and recommendations have been noted before and are not claimed to be exclusively the result of this program. The unique contributions of this effort, relative to the above, are believed to be in (1) quantifying the various trade-offs involved; (2) providing the quantitative basis for selection among various possible implementation approaches, to complement judgment factors which will inevitably be involved in the choice process; and, (3) providing a framework for justifying a chosen course of action in a manner consistent with quarantine program requirements.

Appendix A

Pertinent Mathematical Considerations

Presented herein are the various justifications, mathematical and otherwise, used in the development of the generalized planetary quarantine implementation model discussed in the main body of this report. The individual deviations are itemized in the following presentation and they are sequenced according to the order in which they are referenced in the main text.

Item 1: $P(N) \leq m(r)\, p(g)$

where $P(N)$ = probability that a given lander mission contaminates the planet in question

$m(r)$ = average number of viable organisms released onto the planet from the lander

$p(g)$ = probability that a viable organism, randomly released by the lander onto the planet, grows and spreads during the quarantine period

As indicated in the main text, $P(N)$ is, by definition, expressible in the form*

$$P(N) = P\left\{ N_G \geq 1 \right\}$$

where N_G denotes the (random) number of micro-organisms of terrestrial origin which are deposited by the lander onto the planet's surface or into its atmosphere and subsequently germinate and spread during the period of quarantine. Therefore, in terms of the (random) number, N_R, of viable organisms of terrestrial origin which are released by the

*For convenience, the symbol $P\left\{ (.) \right\}$ is used to denote the probability that the event (.) enclosed within the bracket occurs.

lander onto the planet's surface or into its atmosphere, P(N) may be written in the form

$$P(N) = \sum_{\nu=0}^{\infty} P\left\{N_G \geq 1,\ N_R = \nu\right\}$$

$$= \sum_{\nu=0}^{\infty} P\left\{N_G \geq 1 / N_R = \nu\right\} P\left\{N_R = \nu\right\}$$

The quantity $P\left\{N_G \geq 1 / N_R = \nu\right\}$ in the right-hand side of the preceding expression denotes the conditional probability that $N_G \geq 1$, given that $N_R = \nu$.

Assuming ν viable organisms are released onto the planet and randomly indexing these organisms, the following (characteristic) quantities are defined:

$$X_i = \begin{cases} 1 & , \text{ if the ith organisms grows and spreads} \\ 0 & , \text{ otherwise} \end{cases}$$

$$i = 1, 2, \ldots, \nu$$

In terms of the X_is, the preceding conditional probabilities may be expressed

$$P\left\{N_G \geq 1 / N_R = \nu\right\} = P\left\{X_i = 1 \text{ for some } i = 1, 2, \ldots \nu\right\}$$

$$= 1 - P\left\{X_i = 0 \text{ for } \underline{\text{all}}\ i = 1, 2, \ldots \nu\right\},$$

i.e., given that ν organisms are released, the probability of contamination is equal to one minus the probability that none of the organisms grow and spread during the period of quarantine.

At one "extreme" it can be assumed that the X_i are statistically independent, i.e., the growth and spreading of any one organism is unrelated to the observed behavior of the remaining organisms. In this instance the X_i are independent Bernoulli variables and, for $\nu = 0$,

$$P\left\{X_i = 0 \quad \text{for all } i = 1, 2, \ldots \nu\right\} = \left[1 - p(g)\right]^{\nu}.$$

Furthermore,

$$\left[1 - p(g)\right]^{\nu} \geq 1 - \nu p(g).$$

Combining the preceding expressions it is seen that

$$P(N) \leq \sum_{\nu=0}^{\infty} \nu\, p(g) \;\; P\left\{N_R = \nu\right\}$$

$$\leq p(g)\; m(r)$$

Therefore, if $m(r)$ is no greater than $R/p(g)$, then $P(N)$ is no greater than R and Item 1 applies.

Although the preceding development was based, in part, on the assumption that the X_is were statistically independent, other extremes yield the same result. For example, one may assume that, for any given landing, either all or none of the released organisms grow and spread during the quarantine period. In this instance,

$$P\left\{X_i = 0 \quad \text{for all } i = 1, 2, \ldots \nu\right\} = 1 - p(g)$$

and therefore,

$$P(N) = \sum_{\nu=0}^{\infty} p(g) \;\; P\left\{N_R = \nu\right\}$$

$$\leq p(g) \sum_{\nu=0}^{\infty} \nu\, P\left\{N_R = \nu\right\}$$

$$\leq p(g)\; m(r)$$

Item 2: $m_k(r) \leq m_k(I)\ p_k(r)$

where $m_k(r)$ = Mean number of viable organisms released from the kth source class

$m_k(I)$ = Mean number of viable organisms which arrive at the planet in the kth source location

$p_k(r)$ = Probability that a randomly selected viable organism which arrives at the planet in the kth source location is released

Let $N_k(a)$ = the (random) number of viable organisms which arrive at the planet in the kth source location .

$N_k(r)$ = the (random) number of viable organisms which are released onto the planet from the kth source location.

The mean number released can be expressed in the form

$$m_k(r) = \sum_{\nu=0}^{\infty} \nu \ P\left\{N_k(r) = \nu\right\}$$

$$= \sum_{\nu=0}^{\infty} \nu \sum_{\nu^1=0}^{\infty} P\left\{N_k(r) = \nu / N_k(a) = \nu^1\right\} P\left\{N_k(a) = \nu^1\right\}$$

$$= \sum_{\nu^1=0}^{\infty} \left[\sum_{\nu=0}^{\nu^1} \nu \ P\left\{N_k(r) = \nu / N_k(a) = \nu^1\right\} \right] P\left\{N_k(a) = \nu^1\right\}$$

The quantity enclosed within the square brackets in the preceding expression is equal to the conditional mean number of organisms released, given that ν^1 organisms arrive, i.e.,

$m_k(0)$ = Average loading at the kth source class at the beginning of the time interval of interest

$\Delta m_k(\nu)$ = Average increase in loading at the kth source during the νth subinterval of time

$p_k(s_\nu)$ = Probability that a randomly selected organism, which is located at the kth source location and which is viable at the beginning of the νth subinterval of time, survives throughout the νth subinterval

The (random) number, $N_k(\nu)$, of viable organisms in the kth source class at the end of the νth subinterval of time is expressible in the form

$$N_k(\nu) = N_k(\nu-1) + \Delta N_k^+(\nu) - \Delta N_k^-(\nu)$$

where

$\Delta N_k^+(\nu)$ = (random) number of organisms added to the source class during the νth subinterval

$\Delta N_k^-(\nu)$ = (random) number of organisms in the kth source class which do not survive the subinterval

Taking averages of both sides of this expression produces

$$m_k(\nu) = m_k^*(\nu) + \Delta m_k(\nu)$$

where

$m_k(\nu)$ = average number of viable organisms located in the kth source class at the end of the νth subinterval

$$\sum_{\nu=0}^{\nu^1} \nu \, P\left\{N_k(r) = \nu / N_k(a) = \nu^1\right\} = m_k(r/N_k(a) = \nu^1)$$

or

$$m_k(r) = \sum m_k(r/N_k(a) = \nu^1) \, P\left\{N_k(a) = \nu^1\right\} .$$

As in the case of Item 1, above, one might assume the statistical independence of the release of the viable organisms which arrive at the planet within any one source category, If so, then

$$m_k(r/N_k(a) = \nu^1) = \nu^1 p_k(r)$$

where $p_k(r)$ denotes the probability that a randomly selected viable organism which arrives is released onto the planet. Combining the previous two expressions produces the desired representation, i.e.,

$$m_k(r) = m_k(I) \, p_k(r).$$

Here again, the assumption of statistical independence was used but was not absolutely necessary. For example, if one assumes that either all or none of the arriving organisms will be released (i.e., total correlation) then the preceding expression results.

Item 3: $$m_k(I) = m_k(0) \prod_{\nu=1}^{n_k} p_k(s_\nu) + \Delta m_k(1) \prod_{\nu=2}^{n_k} p_k(s_\nu) + \ldots$$

$$+ \Delta m_k(n_k - 1) p_k(s_{n_k}) + \Delta m_k(n_k)$$

where

$m_k(I)$ = Average number of viable organisms arriving at the planet in the kth source location

$m_k^*(\nu)$ = average number of viable organisms located in the kth source class at the end of the νth subinterval which were there at the beginning of the subinterval

It is conservatively assumed that any organism added to the source class during the subinterval survives at least to the end of the subinterval. Moreover, reasoning similar to that used in the preceding items produces

$$m_k^*(\nu) = m_k(\nu - 1)\, p_k(s_\nu)$$

i.e.,

$$m_k(\nu) = m_k(\nu - 1)p_k(s_\nu) + \Delta m_k(\nu)$$

Combining expressions of the previous form for all values of $\nu = 1,2,\ldots n_k$ results in the desired expression since

$$m_k(I) = m_k(n_k)$$

$$= m_k(n_k-1)p_k(s_{n_k})+\Delta m_k(n_k)$$

$$= m_k(n_k-2)p_k(s_{n_k-1})p_k(s_{n_k})+\Delta m_k(n_k-1)p_k(s_{n_k})+\Delta m_k(n_k) \quad \text{etc.}$$

Item 4: $$p_k(r) = \int_0^\infty P_k(V_I)\, g_k(V_I) \left\{ p_k(r_I/V_I) + \left[1-p_k(r_I/V_I)\right] q(s/e)\, p_k(r_e/V_I) \right\} dV_I$$

where

$p_k(r)$ = Probability that a randomly selected organism, located at the kth (buried) source class and viable at the instant of impact, will be released onto the planet during the period of quarantine

$p_k(V_I)$ = Impact velocity distribution function associated with the kth (buried) source class

$g_k(V_I)$ = Conditional probability that a randomly selected organism from the kth (buried) source class survives impact, given impact velocity V_I

$q_k(s/e)$ = Conditional probability that a randomly selected organism from the kth source class and which survives impact survives erosion mechanism at a particular rate of erosion

$p_k(r_I/V_I)$ = Conditional probability that a randomly selected organism from the kth source class, which survives impact, is released as a result of impact, given impact velocity V_I

$p_k(r_e/V_I)$ = Conditional probability that a randomly selected organism, from the kth source class, which survives impact, is subsequently released as a result of erosion, given impact velocity V_I and given that it is not released as a result of impact and survives erosion

The overall release probability associated with the kth buried source class is expressible in the form

$$p_k(r) = \int_0^\infty p_k^*(r/V_I)\ p_k(V_I)\ dV_I$$

where $p_k^*(r/V_I)$ denotes the conditional probability that a randomly selected organism from the kth source class is released, given impact velocity V_I. In turn, $p_k^*(r/V_I)$ can be written

$$p_k^*(r/V_I) = p_k(V_I)\ g_k(V_I)$$

where $g_k(V_I)$ and $p_k(V_I)$ are as previously defined. It is assumed that release is possible in only two mutually exclusive ways, viz, through the force of impact on the planet and through the post-impact erosion of the source material. Hence, $p_k(r/V_I)$ is expressible by

$$p_k(r/V_I) = p_k(r_I/V_I) + q_k^*(r_e/V_I)$$

where $p_k(V_I)$ is defined previously and where $q_k^*(r_e/V_I)$ denotes the conditional probability that a randomly selected organism from the kth source class is released through erosion, given impact velocity V_I and survival of impact. Finally, for convenience $q_k^*(r_e/V_I)$ is further expressed by

$$q_k^*(r_e/V_I) = \left\{1-p_k(r_I/V_I)\right\} q_k(s/e)\, p_k(r_e/V_I)$$

where $p_k(r_e/V_I)$ is analogous to $q_k(r_e/V_I)$ with the additional condition that the randomly selected organism was not released through impact with the planet. Appropriately combining the preceding expressions then produces the desired relationship. In deriving this relationship we assume the following sequence of events: (1) an organism survives impact; (2) is not release in the process of impact; and, (3) survives the erosion mechanism at a particular rate of erosion and is released by the mechanism of erosion during the quarantine period.

Item 5: $$p_k(r_I/V_I) = \begin{cases} \lambda f_k(V_I) & , V_I \geq V_k^c \\ 0 & , \text{otherwise} \end{cases}$$

where

λ = Exposure depth coefficient

$f_k(V_I)$ = Fracture ratio associated the kth source material and the impact velocity V_I

Prior studies and experiments demonstrate that the probability that a randomly selected organism buried or embedded within

a solid material will be exposed upon fracture of the material is approximately equal to the effective proportion of the solid's interior which is exposed through fracturing. $\lambda f_k(V_I)$ corresponds to this proportion with $f_k(V_I)$ denoting the ratio of the effective area exposed upon impact to the total volume of source material. λ is an assumed constant associated with the effective depth below the newly exposed area to which existing organisms will be exposed.

Appendix B

Computer Model

The program described herein is the result of several months of modification with respect to both the programming method used and the model definition. In this section, however, only the program which was used will be described.

Basically, one program has been exercised. This program was written in the IBM basic programming language for a time shared system and accessed from an ASR 33 teletype terminal. There were, however, a few runs that were made using a slight modification of the program. A description of the program as it was used normally will be given, and available options of the program will be discussed. The discussion is followed by the flow chart and program listing. The input to the program consists of a data matrix, Q. It is convenient to think of this matrix in terms of three sub-matrices. Given that there are n source classes to be considered, the first n rows of Q correspond to the n source classes, and thus constitute the first sub-matrix. The next sub-matrix has many rows to allow for different lander impact velocities. For each of these impact velocities there are four possible values for the fracture ratio coefficient of which the first is defined as unity for mated and interior source classes. The third sub-matrix consists of one row of probabilities such that each column in the row corresponds to the same row in the second sub-matrix and is the probability of impacting at the specified velocity.

In the first sub-matrix, the information contained in each row, corresponding to each source class, consists of initial microbial loading, the ratio of f/a cycle time to terminal sterilization time, the effective D-value during the f/a cycle, the effective D-value during the terminal sterilization, MAST option sterilization time, probability of arrival at the planet, three parameters to indicate that the source is surface, mated, or buried contamination. For buried sources allowance is made for two erosion parameters, the erosion rate for buried contamination, or the amount of recontamination

after the f/a cycle for nonburied sources, and two thermal profile parameters. To separate each of the sub-matrices a value of 999 was entered in the last row and column of each sub-matrix. Otherwise the last column of each sub-matrix contained a zero.

After the data is read into the program from a series of data statements, the user may enter "STOP" or "NO CHANGE IN DATA", and "TSPROFILE" or "NO PROFILE". If the user enters anything else, the program will ask for the row and column of the Q matrix where a change is desired, and it will ask for the new value desired. Modification to individual data values will continue to be accepted in this way until the user inputs 999, X, X where X is an arbitary number. Next, the program computes a matrix W. W represents the probabilities of microbal release when the spacecraft impacts on the planet's surface. Each row of W represents a different impact velocity distribution, while in each row, column elements are grouped according to each possible fracture ratio, each group containing elements for each of the possible critical velocities.

The program next begins a loop that increments the terminal sterilization variable, T3, initially in increments of one hour. For each value of the variable T3, the program loops on each source class using the information in the Q matrix which was mentioned previously to form the transition probabilities for each of the source classes. Of course, only the source classes which are buried would be subjected to an erosion cycle after impact. The program will, at this point, compute the adjusted sterilization time and f/a cycle time. The resulting product of transition probabilities for each source class is multiplied by the initial loading to give the mean number of microbes released onto the planet for that particular source class and placed in the appropriate column of the first row of the matrix R. The source class number is placed in the same column of the second row of R.

The contributions from each source class are summed to give the total contribution for that particular sterilization time T3. If this total contamination is less than a certain acceptable amount (10^{-3}),

the sterilization time loop is executed again to give precision to within 1/10 of an hour. After accuracy to within 1/10 of an hour has been obtained, the program exits from the sterilization time loop. This ends the first phase of the program.

The remainder of the program is concerned with the preparation of results for output and the print-out itself. Initially an input allows the operator to call for options of listing data and/or tracing each source's progression in addition to requesting the number of sources to be ordered and displayed.

This section consists of a contamination release vector reordering procedure, a printout of the KO most dominant sources, and the 'trace'/ 'list' option. After exit from the sterilization time loop a matrix R of dimension 2 x I (1), which contains each source class' released contamination in the first row entry and in the corresponding second row entry the source class number, as it appeared in the input matrix Q, is presented to the reordering section. While the matrix R contains final released contamination, the vector V contains the contamination released only through erosion. However, only R is to be ordered as this ordering is done column-wise with the KO most dominant source, appearing at the first and their corresponding source number in the second row and, thus, the information contained in the V vector corresponding to source class I may be retrieved by printing V(R(2,I)).

In the printout each of the KO most dominant sources are displayed on a single line. Column-wise under respective headings, the source number, original bio-loading, contamination released through erosion, and total released contamination are printed.

Next the required terminal sterilization time is given to the nearest tenth of an hour. If the 'list' option was invoked, the input data for the KO most dominant sources is then printed. Next the programmer may trace the various sources at each stage of the process from F/A to the impact-erosion epoch for terminal sterilization times of 2, 4, 6, 8, ... up to the required terminal sterilization time. In case the trace routine is opted at the second operator intervention, the data 'list' is skipped altogether and the 'trace' is done directly.

The tracing is run by inputing the source class to be traced followed by a comma and the 2-hour interval at which the tracing begins. When no further tracing is desired 0,0 is entered to terminate the 'trace' procedure.

In terms of the computer variables, the model will now be formulated as it appears in the program. Table B-1 relates the computer parameters to those used in Appendix A.

First the probability that a particular viable organism of a particular source class will survive until impact with the planet is given by:

$$T = P_1 \left[10 - \frac{T3}{D1}\left(10 - \frac{T_1 T_3}{D2} + (1 - \delta_k)\frac{Q(k,11)}{Q(k,1)}\right.\right.$$

$$\left.\left. + (1 - \delta_k)\frac{Q(k,10)}{Q(k,1)}\right]\right.$$

The probability of an organism being released upon impact given that it survived until pre-impact and survived impact is given by:

$$T = T\left(\sum_{V_I \geq V_c} \lambda f_k(V_I) \quad P_k(V_I)\right)$$

The erosion factor is given by:

$$U = Q(k,9) + Q(k,10) \sum_{V_I \geq V_c} P_k(V_I) + \sum_{V_I \geq V_c} f_k(V_I) P_k(V_I)$$

Thus, the mean number of microbes contaminating the planet during a quarantine period of T6 years is given by:

$$M(r) = (T - T')\left[(E1\ U\ T\ 6)\ \delta_k + T'\right]\ Q(k,1)$$

where:

$$\delta_k = \begin{cases} 1 & k = 2 \\ 0 & k = 0,1 \end{cases}$$

Variable (model parameter)	Program Designation
$m_k(0)$	Q(k,1) all sources
$\Delta m_k(2)$	Q(k,11) k = 1,2,3
t_{k3}	T3
t_{k2}	Q(k,2), T1
D_{k3}	D1
D_{k2}	D2
$\left\{P_k(V_I \geq V_K^c)\right\}$	W(1,k) k-non - buried
$P_k(V_I)$	Q(7,I)
$\lambda f_k(V_I)$ for K =1,2,3,4 at 0 impact " " " " 1000 "	Q(5, L+1) = 0 Q(6, L+1)
$f_k(0)$	0 all non -buried Q(k,9) buried
$f_k(1)$	0 non - buried Q(k,10) buried
e_k	Q(4,11)
t_q	T6

TABLE B-1

In the above equations, k denotes the particular source class. The remaining variables are defined as follows:

T1 = ratio of F/A cycle time to terminal sterilization time

T3 = Terminal sterilization time

D1 = D_{k3}

D2 = D_{k2}

P1 = probability that the lander craft arrives at the planet

$P_k(V_I)$ = Probability of impact velocity V_I

Q(k,1) = initial mean loading corresponding to source class k

Q(k,9) = 0 for all non-buried sources $f_k^{(0)}$ otherwise

Q(k,10) = $\Delta M_k^{(3)}$ For all non-buried source $f_k^{(1)}$ otherwise

Q(k,11) = $\Delta M_k^{(2)}$ For all non-buried source E1 otherwise

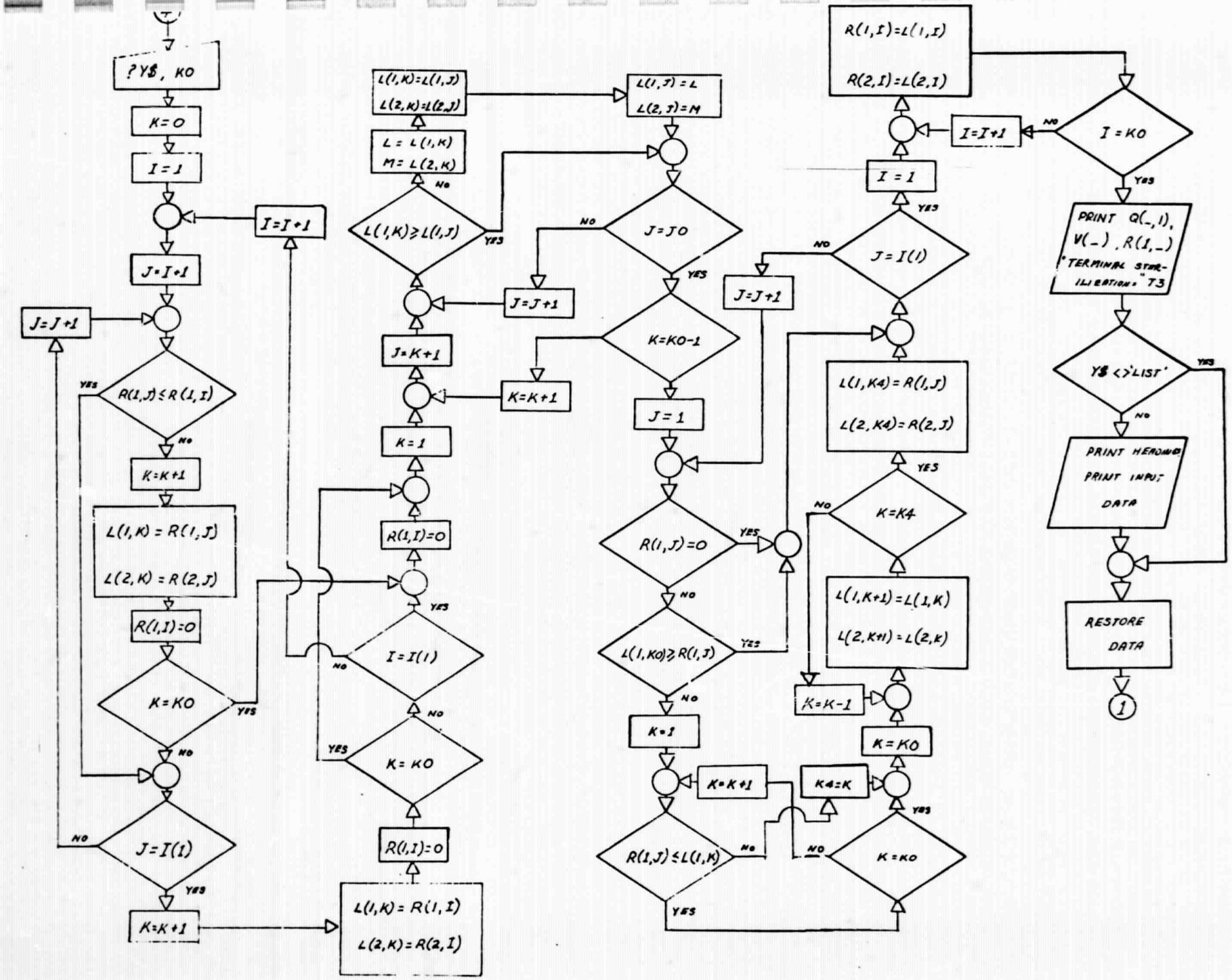
E1 = erosion rate for all buried contamination

T6 = length of quarantine period (yrs)

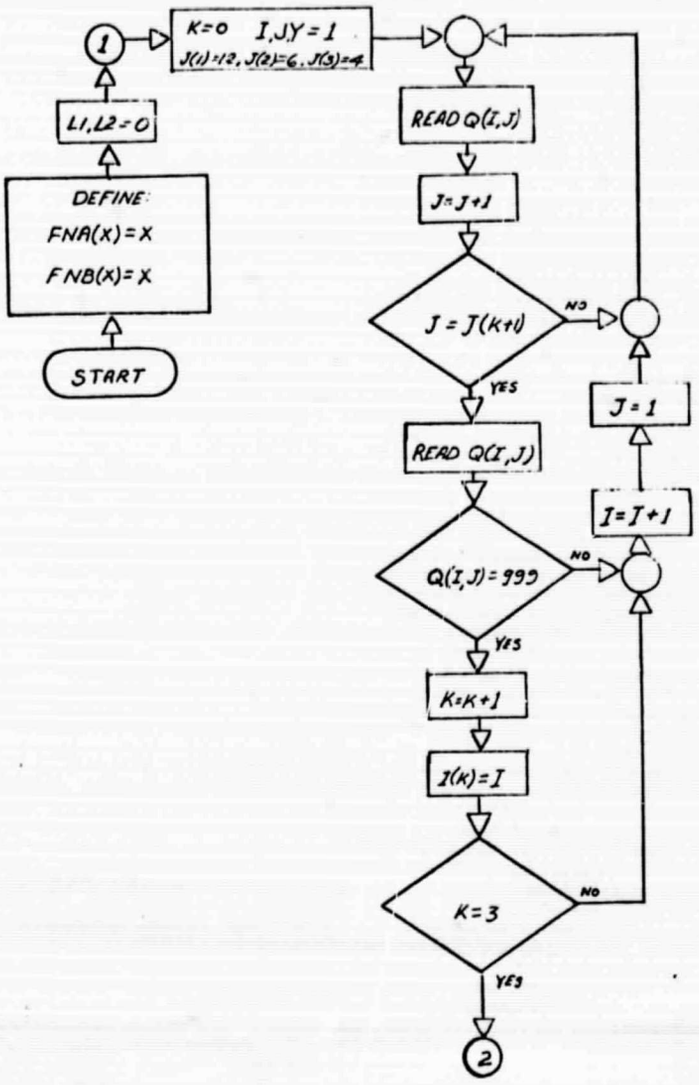
Q(5,1) = $f_k(V_I)$ for K = 1,2,3,4 at an impact of 0 ft/sec

Q(6.1) = $f_k(V_I)$ for K = 1,2,3,4 at an impact of 1000 ft./sec

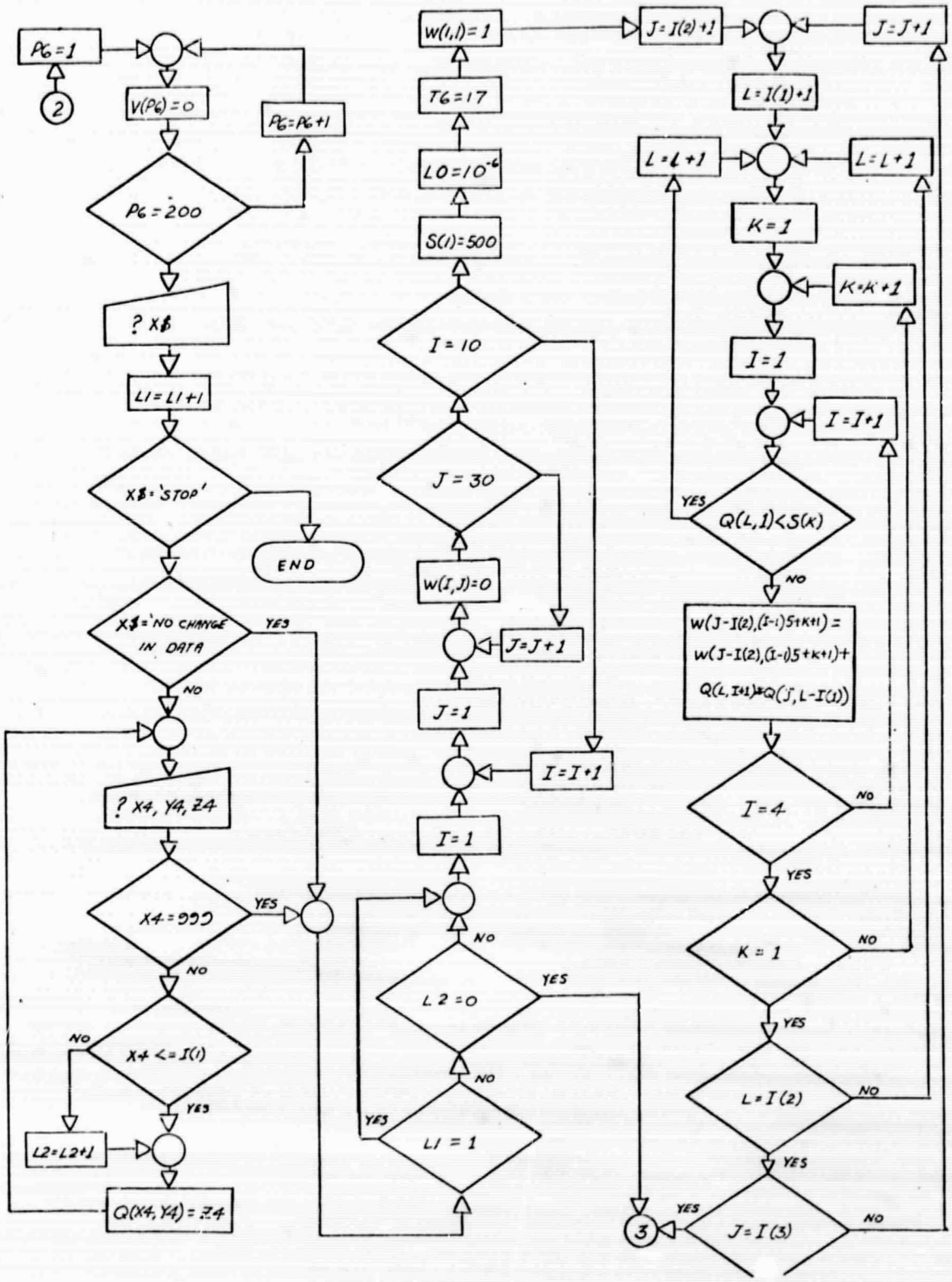
Note from the above that the computer model assumes a total of 4 source classes and two possible impact velocities at 0 and 1000 ft./sec. It is also assumed that there is 1 critical velocity and that it lies between 0 and 1000 ft./sec.


?Y$, KO
K=0
I=1
I=I+1
J=I+1
J=J+1
R(1,J)≤R(1,I)
YES
NO
K=K+1
L(1,K)=R(1,J)
L(2,K)=R(2,J)
R(1,I)=0
K=KO
YES
NO
J=I(1)
YES
NO
K=K+1
L(1,K)=R(1,I)
L(2,K)=R(2,I)
L(1,K)=L(1,J)
L(2,K)=L(2,J)
L=L(1,K)
M=L(2,K)
L(1,K)≥L(1,J)
YES
NO
J=JO
YES
NO
J=J+1
K=KO-1
K=K+1
J=K+1
K=1
R(1,I)=0
I=I(1)
YES
NO
K=KO
YES
NO
R(1,I)=0
L(1,K)=R(1,I)
L(2,K)=R(2,I)
L(1,J)=L
L(2,J)=M
J=1
R(1,J)=0
YES
NO
L(1,KO)≥R(1,J)
YES
NO
K=1
K=K+1
R(1,J)≤L(1,K)
NO
YES
K4=K
K=KO
YES
NO
K=K-1
L(1,K+1)=L(1,K)
L(2,K+1)=L(2,K)
K=K4
YES
NO
L(1,K4)=R(1,J)
L(2,K4)=R(2,J)
J=J+1
J=I(1)
YES
NO
I=1
I=I+1
I=KO
YES
NO
R(1,I)=L(1,I)
R(2,I)=L(2,I)
PRINT Q(_,I), V(_), R(I,_) "TERMINAL STERILIZATION" T3
Y$<>'LIST'
YES
NO
PRINT HEADING PRINT INPUT DATA
RESTORE DATA
1

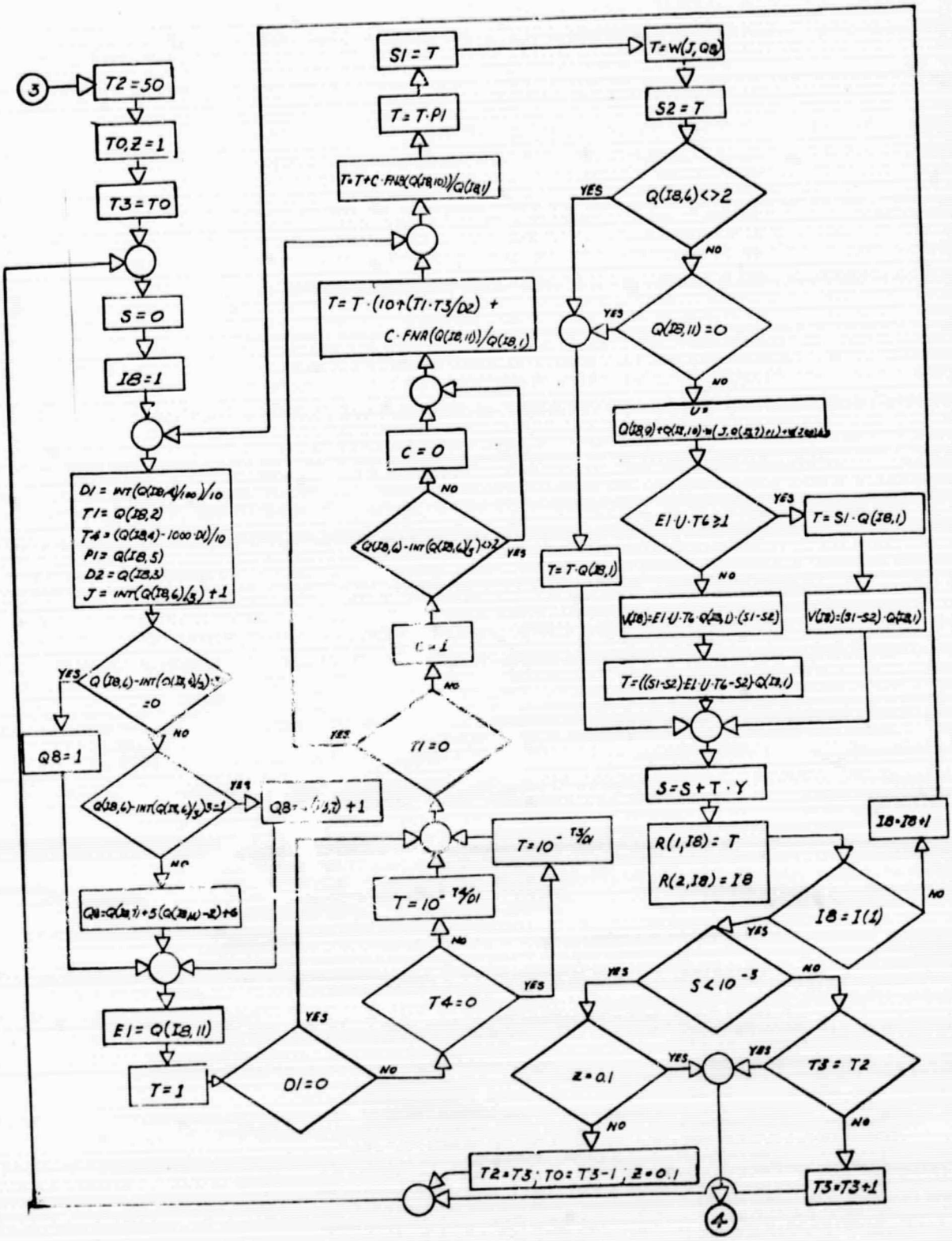
FLOW CHART



FLOW CHART (CONT'D.)



FLOW CHART (CONT'D.)



FLOW CHART (CONT'D.)

COMPUTER PROGRAM

```
141 REM...LOAD DATA FROM 1 THRU I(1) SOURCES,I(1)+1 THRU I(2) CRITICAL.
142 REM...VELOCITIES WITH J(2)-2 RESPECTIVE FRACTURE RATIOS,J(2)+1 THRU.
143 REM...I(3) DIFFERENT P(V) CURVES WITH J(2)-J(1) ENTRIES.
145 REM...THE "999" SIGNALS THE END OF A DATA BLOCK.
149 DIM E(15,50)
150 DIM L(2,50),Q(50,12),R(2,50),V(50),W(10,30)
151 DIM A(15,50),B(15,50),C(15,50),D(15,50)
152 DEF FNA(X)=X
153 DEF FNB(X)=X
154 DEF FNC(X)=X
155 L1,L2=0
180 Y=1
190 K=0
200 I,J=1
210 J(1)=12
220 J(2)=6
230 J(3)=4
240 READ Q(I,J)
250 J=J+1
260 IF J=J(K+1 ) THEN 280
270 GO TO 240
280 READ Q(I,J)
290 IF Q(I,J)=999 THEN 330
300 I=I+1
310 J=1
320 GO TO 240
330 K=K+1
340 I(K)=I
350 IF K=3 THEN 390
360 I=I+1
370 J=1
380 GO TO 240
385 REM...
386 REM...INSTRUCTIONS FOR MODE OF RUNNING PROGRAM.
387 REM...
389 REM...
390  FOR P6=1 TO 50
392 V(P6)=0
394 NEXT P6
400 INPUT X$
402 L1=L1+1
405 IF X$='STOP' THEN 2330
410 IF X$='NO CHANGE IN DATA' THEN 455
420 INPUT X4,Y4,Z4
430 IF X4=999 THEN 455
435 IF X4<=I(1) THEN 440
437 L2=L2+1
440 Q(X4,Y4)=Z4
450 GO TO 420
455 IF L1=1 THEN 462
460 IF L2=0 THEN 630
462 FOR I=1 TO 10
464 FOR J=1 TO 30
466 W(I,J)=0
```

```
468 NEXT J
470 NEXT I
490 S(1)=500
505 LO=1E-6
510 T6=17
514 REM...
515 REM...COMPUTE MATRIX OF SUMMATIONS OF P(V)'S AND F*P(V)'S.
516 REM...
520 W(1,1)=1
530 FOR J=I(2)+1 TO I(3)
540 FOR L=I(1)+1 TO I(2)
550 FOR K=1 TO 1
560 FOR I=1 TO 4
570 IF O(L,1)<S(K) THEN 610
580 W(J-I(2),(I-1)*5+K+1)=W(J-I(2),(I-1)*5+K+1)+O(L,I+1)*O(J,L-I(1))
590 NEXT I
600 NEXT K
610 NEXT L
620 NEXT J
621 REM...
622 REM...CYCLE ON STERILIZATION TIME UNTIL M(R)<REQUIREMENT.
623 REM...
630 T2=30
640 Z,TO=1
650 FOR T3=TO TO T2 STEP Z
651 XO=0
652 BO,B1,B2,B3,B4,B5,B6,B7,B8,B9=0
654 IF T3<2 THEN 660
656 IF Z=.1 THEN 660
657 IF (T3/2)-INT(T3/2)<>0 THEN 660
658 XO=1
660 S=0
670 FOR I8=1 TO I(1)
680 D1=INT(O(I8,4)/100)/10
690 T1=INT(O(I8,2)/100)
700 T4=(O(I8,4)-1000*D1)/10
710 P1=O(I8,5)
720 D2=(O(I8,2)-T1*100)/10
722 T5=INT(O(I8,3)/100)
723 D3=(O(I8,3)-T5*100)/10
730 J=INT(O(I8,6)/3)+1
740 IF O(I8,6)-INT(O(I8,6)/3)*3=0 THEN 800
750 IF O(I8,6)-INT(O(I8,6)/3)*3=1 THEN 780
760 O8=O(I8,7)+5*(O(I8,8)-2)+6
770 GO TO 810
780 O8=O(I8,7)+1
790 GO TO 810
800 O8=1
810 E1=O(I8,11)
812 C=1
813 T=O(I8,1)
814 IF O(I8,6)-INT(O(I8,6)/3)*3<>2 THEN 818
816 C=0
818 IF T1=0 THEN 830
```

```
820 T=T*10↑(-T1/D2)
822 IF X0=0 THEN 826
824 E(T3/2,I8)=T
826 B3=C*FNC(Q(I8,9))
828 T=T+B3
830 IF T5=0 THEN 860
832 T=T*10↑(-T5*T3/D3)
834 IF T>1E-74 THEN 837
837 IF X0=0 THEN 850
839 A(T3/2,I8)=T
850 B0=C*FNA(Q(I8,11))
855 T=T+B0
860 IF T4<>0 THEN 880
862 IF D1=0 THEN 868
865 T=T*10↑(-T3/D1)
868 IF X0=0 THEN 895
870 B(T3/2,I8)=T
875 GO TO 895
880 T=T*10↑(-T4/D1)
885 B(T3/2,I8)=T
895 B1=C*FNB(Q(I8,10))
900 T=T+B1
905 T=T*P1
910 S1=T
920 T=T*W(J,08)
930 S2=T
932 IF X0=0 THEN 940
935 C(T3/2,I8)=T
940 IF Q(I8,6)<>2 THEN 1050
950 IF Q(I8,6)=0 THEN 1050
960 U=Q(I8,9)+Q(I8,10)*W(J,Q(I8,7)+1)+W(J,08)/L0
970 IF E1*U*T6>=1 THEN 1010
980 V(I8)=E1*U*T6*(S1-S2)
990 T=(S1-S2)*E1*U*T6+S2
1000 GO TO 1050
1010 T=S1
1020 V(I8)=S1-S2
1030 GO TO 1050
1050 S=S+T*Y
1053 IF X0=0 THEN 1060
1055 D(T3/2,I8)=V(I8)
1060 R(1,I8)=T
1070 R(2,I8)=I8
1080 NEXT I8
1090 IF S<10↑(-3) THEN 1120
1100 NEXT T3
1110 GO TO 1170
1120 IF Z=.1 THEN 1170
1130 T2=T3
1140 T0=T3-1
1150 Z=.1
1160 GO TO 650
1161 REM...
1162 REM...INSTRUCTIONS FOR DATA PRINT AND NUMBER OF SOURCES TO BE.
```

```
1163 REM...ØRDERED AND PRINTED.
1164 REM...
1170 INPUT Y$,K0
1171 REM...
1172 REM...RE-ØRDER CØNTAMINATIØN RELEASE VECTØR BY DECREASING.
1173 REM...MAGNITUDE.
1174 REM...
1190 K=0
1200 FØR I=1 TØ I(1)
1210 FØR J=I+1 TØ I(1)
1220 IF R(1,J)<=R(1,I) THEN 1280
1230 K=K+1
1240 L(1,K)=R(1,J)
1250 L(2,K)=R(2,J)
1260 R(1,J)=0
1270 IF K=K0 THEN 1350
1280 NEXT J
1290 K=K+1
1300L(1,K)=R(1,I)
1310 L(2,K)=R(2,I)
1320 R(1,I)=0
1330 IF K=K0 THEN 1360
1340 NEXT I
1350 R(1,I)=0
1360 FØR K=1 TØ K0-1
1370 FØR J=K+1 TØ K0
1380 IF L(1,K)>=L(1,J) THEN 1450
1390 L=L(1,K)
1400 M=L(2,K)
1410 L(1,K)=L(1,J)
1420 L(2,K)=L(2,J)
1430 L(1,J)=L
1440 L(2,J)=M
1450 NEXT J
1460 NEXT K
1470 FØR J=1 TØ I(1)
1480  IF R(1,J)=0 THEN 1610
1490 IF L(1,K0)>=R(1,J) THEN 1610
1500 FØR K=1 TØ K0
1510 IF R(1,J)<=L(1,K) THEN 1540
1520 K4=K
1530 GØ TØ 1550
1540 NEXT K
1550 FØR K=K0 TØ K4 STEP -1
1560 L(1,K+1)=L(1,K)
1570 L(2,K+1)=L(2,K)
1580 NEXT K
1590 L(1,K4)=R(1,J)
1600 L(2,K4)=R(2,J)
1610 NEXT J
1620 FØR I=1 TØ K0
1630 R(1,I)=L(1,I)
1640 R(2,I)=L(2,I)
1650 NEXT I
```

```
1660 PRINT
1670 PRINT USING 1680
1680:  SOURCE NO.          M(O)          M(R)-EROSION        M(R)-TOTAL
1690 FOR I=1 TO KO
1700 PRINT R(2,I),Q(R(2,I),1),V(R(2,I)),R(1,I)
1710 NEXT I
1720 PRINT
1730 PRINT"REQUIRED STERILIZATION TIME="T3"HOURS"
1740 PRINT
1745 IF YS='TRACE' THEN 1852
1750 IF YS<>'LIST' THEN 1870
1760 PRINT
1770 PRINT
1780 PRINT"INPUT PARAMETERS"
1790 PRINT
1800 PRINT USING 1810
1810: LOAD  T(F/A)  D(F/A)  D(TS)-TO  P(A)  A  B  C    FO     F1     E1
1820 FOR J=1 TO KO
1830 I=R(2,J)
1840 PRINT USING 1850 ,Q(I,1),Q(I,2),Q(I,3),Q(I,4),Q(I,5),Q(I,6),Q(I,7),
Q(I,8),Q(I,9),Q(I,10),Q(I,11)
1850:#.!!!!   ##       ##       ####    #.#   #  #  #  #.!!!! #.!!!! #.!!!
!
1851 NEXT J
1852 PRINT"SOURCE";
1853 INPUT J,E
1854 IF J=0 THEN 1880
1855 FOR I=E TO INT(T3) STEP 2
1856 PRINT"       "I"HOURS"
1857 PRINT"LOAD AT END OF P.P.="E(I/2,J)
1858 IF Q(J,6)=2 THEN 1860
1859 PRINT"BUILD-UP AFTER P.P.="Q(J,9)
1860 PRINT"LOAD AT END OF F/A="A(I/2,J)
1861 IF Q(J,6)=2 THEN 1863
1862 PRINT"BUILD-UP AFTER F/A="                    Q(J,11)
1863 PRINT"LOAD AT END OF T.S.="B(I/2,J)
1864 IF Q(J,6)=2 THEN 1866
1865 PRINT"BUILD-UP AFTER T.S="                    Q(J,10)
1866 PRINT"RELEASE THRU IMPACT="C(I/2,J)
1867 PRINT"RELEASE THRU EROS.="D(I/2,J)
1868 NEXT I
1869 GO TO 1852
1870 PRINT
1880 PRINT
1890 DATA 1E7,305,005,500,1,1,0,0,1E6,0,0,0
1900 DATA 1E7,305,005,500,1,1,1,1,1E6,0,0,0
1910 DATA 1E7,310,010,1000,1,1,1,1,1E5,0,0,0
1920 DATA 1E7,350,050,5000,1,2,1,2,10,10,1E-6,999
2000 DATA 0,1,0,0,0,0
2010 DATA 1000,1,1E-4,0,0,999
2020 DATA .9,.1,0,999
2310 RESTORE
2320 GO TO 180
2330 END
```

GLOSSARY OF TERMS

$A_k^{(o)}$ - Area exposed assuming no break up of the craft

$A_k^{(1)}(V_I)$ - Additional area exposed as a result of the source material breaking away from the craft

$A_k(V_I)$ - Additional area exposed as a result of fracturing of the source material

$\bar{A}_k(V_I)$ - Surface area exposed to the planets' atmosphere

$D_{k\nu}$ - Microbial resistance associated with the k-th source class during ν-th heat cycle (at 125^oc)

e_k - Erosion rate associated with the k-th source class

$f_k(V_I)$ - Fracture ratio, the area newly exposed per unit volume of k-th source class

$g_k(V_I)$ - Conditional probability that a randomly selected organism from the k-th (buried) source class survives impact, given impact velocity V_I.

$m(r)$ - Mean number of viable organisms released onto the planet

$m_k(r)$ - Average number of organisms released from the k-th source

$m_k(I)$ - Mean number of organisms located on the k-th source at the instant of impact

$m_k(o)$ - Average loading of the k-th source class at the beginning of the time interval of interest

$\Delta m_k(\nu)$ - Average increase in loading of the k-th source class during the ν-th subinterval of time

n_s - Number of contamination sources on the lander

$P(N)$ - Probability that a lander will contaminate planet

$P(g)$ - Probability that a viable organism grows and spreads during quarantine period

$p_k(r)$ - Probability that a randomly selected organism located in the k-th source class at the instant of impact will be released between that instant and the termination of the quarantine period

$P_k\ (s_\nu)$ - Probability that a randomly selected organism which is located in the k-th source class survives the ν-th subinterval (conditional upon previous survival)

$P_k\ (V_I)$ - Impact velocity distribution function associated with the k-th (buried) source class

$p_k\ (r_I/V_I)$ - Conditional probability that a randomly selected organism, taken from the k-th source class and which survives impact, is released as a result of impact, given impact velocity V_I.

$p_k\ (r_e/V_I)$ - Conditional probability that a randomly selected organism, taken from the k-th source class and surviving impact, is subsequently released as a result of erosion, given impact velocity V_I and given that it is not released as a result of impact, and survives erosion.

$q_k\ (s/e)$ - Conditional probability that a randomly selected organism from the k-th source class and which survives impact, survives erosion mechanism at a particular rate of erosion

R - Prescribed maximum allowable value for P (N)

t_q - Time between impact and termination of quarantine period

$t_{k\nu}$ - The effective time at which heat is applied at 125^oc

V_k - Volume of material in the k-th source class

V_I - Impact velocity of lander

V_k^c - Critical impact velocity associated with the k-th source class

λ - Effective depth of exposure

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