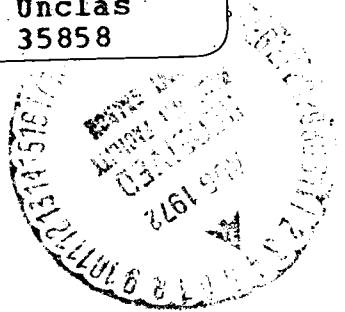(NASA-CR-127467) MICROBIAL BURDEN
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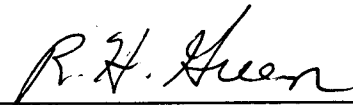
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MICROBIAL BURDEN PREDICTION MODEL
FOR UNMANNED PLANETARY SPACECRAFT
(FINAL REPORT)

June 30, 1972

A. R. Hoffman

D. A. Winterburn (Bionetics Corp.)

APPROVED BY:

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PREFACE

This document contains a report on one phase of Research and
Advanced Development carried out at the Jet Propulsion Laboratory,
California Institute of Technology, under Contract No. NAS 7-100,
sponsored by the National Aeronautics and Space Administration.

CONTENTS

TABLES

ABSTRACT

This report details the technical development of a computer program for predicting microbial burden on unmanned planetary spacecraft. The discussion includes the derivation of the basic analytical equations, the selection of a method for handling several random variables, the macrologic of the computer programs and the validation and verification of the model. The prediction model has been developed by the Jet Propulsion Laboratory as an analytical tool which 1) supplements the biological assays of a spacecraft by simulating the microbial accretion during periods when assays are not taken, 2) minimizes the necessity for a large number of microbiological assays, and 3) predicts the microbial loading on a lander immediately prior to sterilization and other non-lander equipment prior to launch.

It is shown that these purposes not only have been achieved but also that the prediction results compare favorably to the estimates derived from the direct assays. The computer program can be applied not only as a prediction instrument but also as a management and control tool. The basic logic of the model is shown to have possible applicability to other sequential flow processes, such as food processing.

1. <u>Biologically Significant Zone</u>: A zone for which the burden accumulation process differs considerably from that of other zones due to differences in orientation, surface material, contact, etc.

2. <u>Bump</u>: The portion of the discrete probability density function (pdf) represented by an area between two class limits, (Figure 1). The ordinate value, i.e., probability, is assumed constant between the class limit points.

3. <u>Class (cell)</u>: A convenient division of the range of a variate.

4. <u>Class Limits or Boundaries</u>: The variate values which determine the upper and lower limits of a class.

5. <u>Clean Room</u>: A room provided with special air filters to reduce airborne particles; special clothing is also required to reduce the shedding of particles from skin and hair. Clean rooms are usually classified according to the maximum number of allowable particles (0.5 micron and larger) per cubic foot of air; Class 100 and Class 100,000 are most common. A laminar flow clean room has a relatively high airflow in one direction only; such flow can be either crossflow (from one end of the room to the other) or downflow (from ceiling to floor).

6. <u>Exposed Surface Burden</u>: The viable organisms existing on the exterior exposed surface of an item.

7. <u>Exposed Surfaces</u>: Those surfaces of an assembly, subsystem, or system that would be illuminated if placed at the center of an inwardly directed luminous sphere.

8. Histogram: A representation of the discrete probability density function (pdf) of a random variable, x. For the purposes of this report the histograms (pdfs) include but are not limited to representation of the probability of occurrence versus the number of microorganisms. A graphical representation is shown in the figure below.
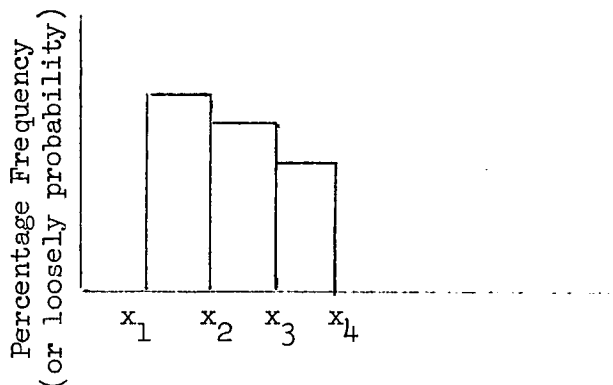
Figure 1. Sample Histogram

9. Histogram Combining Method: A numerical technique for performing arithmetic operations of addition, multiplication, and division, on histograms.

10. Initial Burden: The burden present on an assembly at the time the assembly is integrated into its zone. The assembly initial burden is a function of its history for the period from completion of the Flight Acceptance sterilization test to, but not including, integration of the assembly to its zone during probe buildup.

11. Level of Activity: One of four levels of detail in the representation of an assembly and test sequence to be simulated by the burden prediction model; (Ref. Vol. VII, P. 2) these levels, in order of increasing detail, are:

First level	(STAGE)
Second level	(TASK)
Third level	(SUBTASK)
Fourth level	(OPERATION)

12. Mated Surface Burden: The viable organisms trapped between mated surfaces such as under screws and in joints.

13. <u>Mated Surfaces</u>: Those occluded surfaces of an assembly, subsystem or system that are formed by mechanically joining two surfaces.

14. <u>Occluded Surfaces</u>: Those surfaces of an assembly, subsystem, or system that are not exposed surfaces. (Note that mated surfaces are a subset of the occluded surfaces.)

15. <u>Sensitivity Study</u>: A computer run to determine the sensitivity of the final predicted burden to a change in a selected input parameters.

16. <u>Spores</u>: Microorganisms in a dormant, resistant state. Sample counts for spores are generally obtained by heating the sample (heat shock) to destroy vegetative organisms.

17. <u>Vegetative Organisms</u>: Microorganisms actively engaged in growth and reproduction. Due to the culture techniques normally used, the sample counts for vegetative organisms may include spores as well.

18. <u>Zone</u>: A portion of the spacecraft that may be uniquely identified by consideration of such things as functional attributes of a subsystem, geometry, and thermal behavior.

I. INTRODUCTION

An important parameter in determining the duration of a terminal steril-
ization cycle for a planetary lander spacecraft is an estimate of the microbial
burden on the spacecraft (buried burden, or mated and exposed surface burdens).
(Ref. 1). For unmanned planetary flyby's and orbiters, the planetary quarantine
analyses may require estimates of microbial burden on spacecraft surfaces.
(Ref. 2 and 3).

As Brown et al (1970) (Ref. 4) noted, there are two models that may be
defined for making these estimates.

Prediction Model - an analytical structure for the estimation of
biological contamination in prescribed regions of the spacecraft wherein
the estimate at a desired point in time prior to sterilization or decontam-
ination is derived from input data obtained at earlier times either by
measurement or estimation. The principal role of the model is to extra-
polate in time the interaction of contamination sources and pertinent
activities to predict the later bio-load state.

Direct Assay Model - an analytical technique for the specification of
biological assay and integration of the resultant data into a valid estimate
of the biological contamination in specified regions of the spacecraft
applicable to the time at which the assays are performed. The model should
provide valid measures of the statistical reliability of the estimates it
generates.

Brown (et al) recommended that "... a prediction model, validated and
verified on a continuing basis by direct assay methods, be used to complement

direct assay estimation where the latter is not applicable because of constraints on accessibility in terms of spacecraft locations or in time."

This report presents a detailed technical description of the JPL microbial burden prediction model and includes the derivation of the basic equations, the selection of a method for handling several random variables, the macrologic of the computer programs and the validation and verification of the model.

Prior to and during the active portion of this task other organizations developed microbial burden prediction models. Among these, is the math model developed by T. Rider of AVCO for F. Farmer at Langley Research Center. (Ref. 5). All of these models consist of sequential flow analysis of the assembly and test of the spacecraft and are based on birth and death processes. Differences among the models include the level at which the burden accretion processes are being tracked and the method for handling random variables .

The impetus for developing a JPL microbial burden prediction model was brought about by the Voyager program during the middle 1960's. The initial funding was from Voyager. Subsequent funding was from the Planetary Quarantine Office of NASA's Office of Space Science. A chronology of the significant milestones during the development of the JPL burden prediction model is given in Table 1.

II. FORMULATION

A. Activity Levels

To identify the sources of burden accumulation during spacecraft assembly and test and to relate these in a one to one manner to the specific activities being performed, a sequential flow analysis of spacecraft

Table 1. Chronological Development of the Microbial Burden Prediction Model

Milestone	Description of Work	JPL Contract Number	Program Manager (MMC)	Contract Monitor (JPL)	When Performed
RFP	Request for Proposals for Phases I-III, Response, and Evaluation	---	R. Meuser	A. Hoffman	March to Aug. '67
Phase I	Determine Generalized Assembly and Test Sequence				
Phase II	Formulate Mathematical Expressions	952028	R. Meuser	A. Hoffman/ E. Sherry	Aug '67 to May '68
Phase III	Develop Computer Model and Apply to MMC Voyager				
Phase IV	Revised Histograms				
Phase V	MV 67-2 Planned Sequence Prepared and Exercised	952028 Follow-on 1	R. Meuser	E. Sherry	June to Dec '68
Phase VI	MV 67-2 Actual Sequence Prepared and Exercised				
Phase VII	Code Modification and Improvement	952532	B. Nelson	E. Sherry/ A. Hoffman	Jul to Nov '69
Phase VIII	Input Translator Program Constructed and MM 69-3 Actual Sequence Prepared and Exercised	952532 Follow-on 1	L. Farabee	A. Hoffman	Dec '69 to May '70
Phase IX	Refined Method of Combining Histograms	952532 Follow-on 2	L. Farabee	A. Hoffman	May to Sept '70
MM '71 Part A	MM '71 Planned Sequence Prepared and Exercised	---	---	A. Hoffman*	May to Oct '70
Part B	MM '71-2 Near Real Time Emulation Prepared and Exercised	---	---	A. Hoffman*	Oct '70 to May '71
Part C	MM '71-2 Actual Sequence Histogram Update and Sensitivity Studies	---	---	A. Hoffman*	May '71 to Jan '72
Documentation	Write Final Report and Users Manual	---	---	A. Hoffman* *Principal Invest.	Nov '71 to Jan '72

operations was performed. A typical lander capsule assembly and test flow (i.e. Level 1 activity) is shown in Fig. 2. Level 2 activity is represented by each box in this figure. For example, a typical Level 2 activity for the lander capsule is the mechanical and electrical buildup of the lander package. A Level 3 activity can be represented by the installation of the radio module into the lander support structure. Level 4 activity is shown in Fig. 3. At the fourth level the analyst was able to identify the sources of burden accumulation and relate these in a one to one manner to the specific activity being performed. This resulted in performing a time and motion study on the assembly operations.

Consider, for instance, the insertion of a bolt to attach the radio module to the structure chassis (Fig. 3). In such an operation, a worker in a specified environment would insert (handle) the bolt; this activity would result in contact with the hardware and would require a given amount of time. Thus a one to one relationship was established between the operation (bolt insertion) and the sources of burden accumulation (environment, personnel, and contact). In the burden prediction model, the four levels are STAGE, TASK, SUBTASK, and OPERATION which correspond to Levels 1, 2, 3, and 4, respectively. Generally, the operations were found to be repetitive, which made it possible to define a minimum number of generic operations that could be used to describe any activity performed in the assembly and test of the spacecraft. These generic operations represented the modular elements used to develop the burden model. A list of these repetitive operations for the Mariner '71 emulation is given in Appendix E.
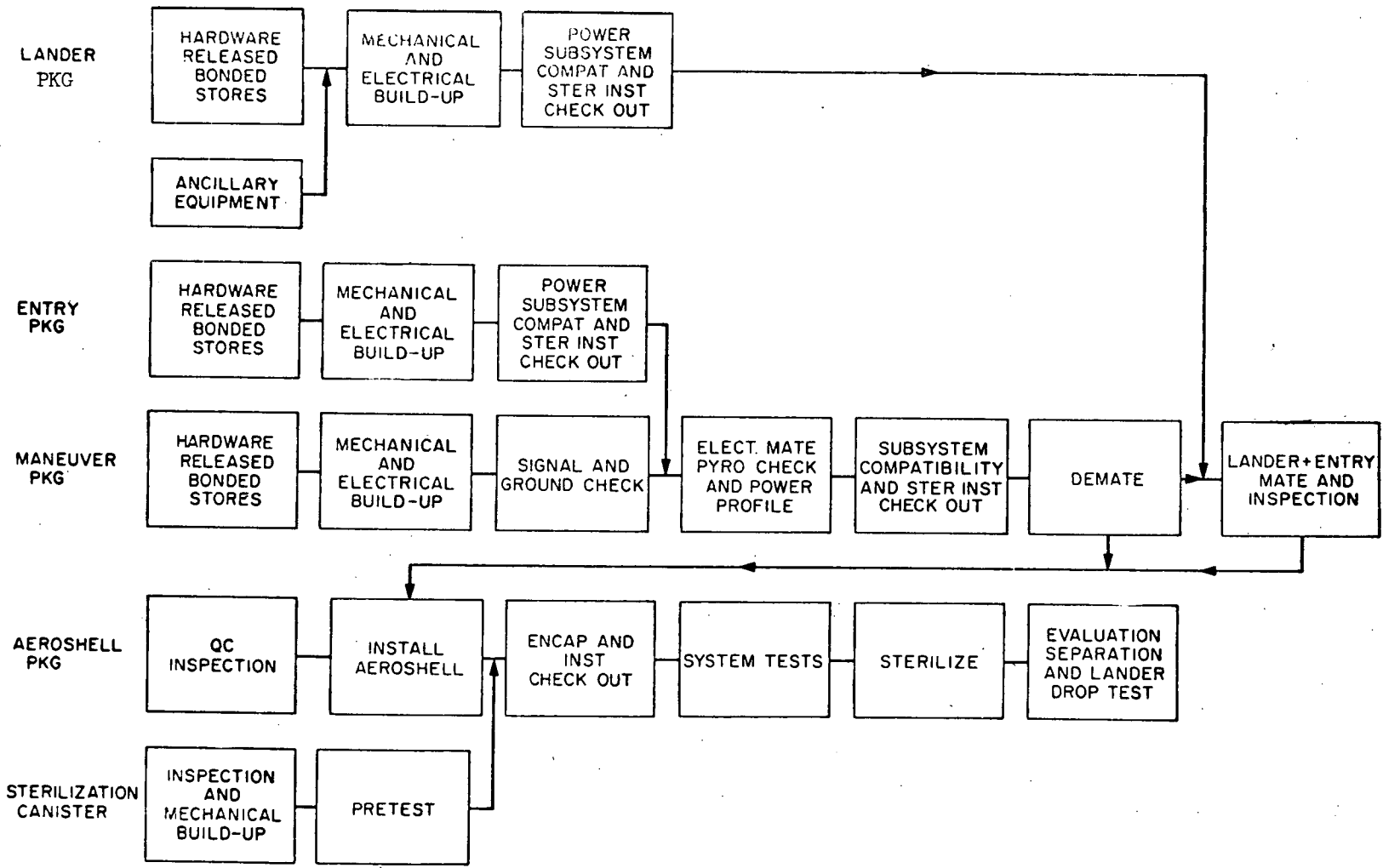
Figure 2. Typical Lander Capsule Assembly and Test Flow

ANALYSIS OF ASSEMBLY OPERATIONS

I	II	III
Place Radio Module Into Chassis	Align And Start Bolt No. 1	Align And Start Bolt No. 2
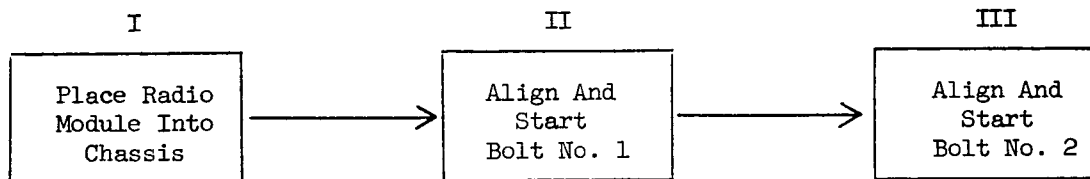
1. Class 100 Clean Room

2. 15 seconds

3. a) 1 sq. in. of Transmitter Contacted by Hand Screw

   b) 180 sq. in. of Area Exposed to Fallout

4. Screws

5. 1 Person, Cap, Gown, Gloves
   2 Gloved Fingers

MICROBIOLOGICAL BURDEN HISTOGRAMS

Fall Out/Unit Area

(100,000 Clean Room, 15-sec Exposure, 1 Capped, Gowned, Gloved Person)

Hand/Bolt Transfer/ Unit Area

(100,000 Clean Room, 15-sec Exposure, 1 Capped, Gowned, Gloved Person)

Tool Transfer/Unit Area

(Transmitter Bolt, 15 sec)

Figure 3. Example of Level 4 Activity

B. <u>Development of Analytical Expressions</u>

1. The purpose of performing the sequential flow analysis was to identify all significant factors that could affect the microbial burden on hardware. The list of factors resulting from this identification is given in Table 2. These parameters generally pertained to one of four characteristics of a given activity:

    a. the environment in which it is performed;

    b. the personnel performing the work;

    c. the type of operations being performed;

    d. the types of organisms being considered.

2. The accumulation process selected as most significant included environmental fallout, personnel and equipment fallout (shedding), and contact by tools or personnel.

These selections were based on information available in the literature, conversations with knowledgeable people, and engineering judgement. Each process was analyzed to determine pertinent parameters and to derive mathemathical expressions relating the appropriate variables.

In addition to the three burden accumulation process, a mathematical expression was developed to represent burden reduction. This process is termed "decontamination", and includes physical removal of organisms (e.g. by vacuum cleaning) as well as destruction of organisms (e.g. by chemical solvents)

A summary of fundamental assumptions made during the development of the analytical expressions and the computer program is given in Appendix A.

    a. <u>Environmental Personnel and Equipment Fallout</u>

        In a given spacecraft assembly and test environment, it is assumed that viable organisms exist in the air. Due to the actions,

Table 2. Parameters That Affect Microbial Burden

1. Environment

Clean Room Specifications

    Temperature
    Humidity
    Ingress and egress
    Airflow velocity
    Personnel cleanliness
    Clothing

Number of People in the Room

Room Size (floor area, volume)

Organisms/cu ft of Air

2. Personnel

General Biota-Contributing Tendency

    Shedding (hair, skin)
    Breath
    Touch
    Clothing

Personal Affectations (head scratching, etc)

Amount of Movement and Level of Exertion

Mental Attitude

3. Operations

Type of Operation

Biota Level on Tools and Equipment

Area of Contact

Type of Contact (pressure, rubbing, etc)

Position of Worker (above, beside, or under the work)

Orientation of Surfaces

Surface Materials and Finishes (tools and work) including
  Any Chemical Treatment

Number of Men Required

Number of Times This Operation is Repeated

Any Special Requirements (such as protective covers)

Time Required to Perform the Operation

4. Types of Organisms

Spores/Vegetative Organisms

Aerobes/Anaerobes

gravity and airflow, these organisms would tend to settle on exposed surfaces in the environment and hence continually add to the burden on the surface. If there were no loss of these organisms (due to death or physical removal), the surface burden would increase steadily as long as the surface remained in that environment. It was assumed, however, that a burden equilibrium or "plateau" is reached in a given environment after approximately one week. This assumption was based on the experimental results reported in References 6 and 7. The experiment involved placing a tray of sterile stainless steel coupons in the desired environment and assaying a portion of these at selected intervals. In nearly every instance where this was done, it was clear that after a week the coupons had reached a burden "plateau". The only change observed in later samples was attributed to statistical fluctuation. This implies the existence of a mechanism that tends to decrease the number of organisms.

During any short period of time dt, organisms will be deposited on the surface from the air; let R be the rate of deposit, $\frac{\text{organisms}}{\text{sq ft-hr}}$. Since dt is small, R will be constant over this interval of time. During dt there is also a loss of organisms due to an undetermined mechanism. If it is assumed that organisms remain on the surface an average of v hours, then $1/v$ of the population is lost each hour. Thus, allowing $b(t)$ be the number of organisms/sq ft present on the surface at time t, we have $\frac{db}{dt} = R - \frac{1}{v} b$. If the initial ($t = 0$) burden concentration (organisms/sq ft) is denoted by b_o, then this

equation has the solution:

$$b(t) = b_o e^{-t/v} + Rv(1 - e^{-t/v}).$$ (Equation 1)

This becomes the basis for the formula used in the burden prediction model to predict the surface burden that accumulates from the environment.

The rate of deposit of organisms from the air R is assumed to be the sum of two fallout rates, environmental and personnel. The environmental fallout rate is a complicated function of time, surface adhesion characteristics of the deposited particles, relative position of equipment in the area, activity level, and "cleanliness" of the air. For the purpose of this study it is assumed that the environmental fallout rate is simply the product of a surface retention factor, g; fallout velocity of airborne particles (organisms), F_i; and airborne organism concentration, c. The function f_i represents the fallout velocity (ft/hr) of airborne organisms due to airflow and gravity settling; i = 1,2,... Several different values of f_i may be included because the surface of space-craft hardware can be vertically positioned, horizontally positioned or slanted. There is a significant difference in burden accumulation between horizontal and vertical exposed surfaces. Thus f_1 will be used for exposed surfaces facing upward and f_2 for other surfaces. These two functions are constant in a given environment and are assumed measureable. The function g represents the fraction of particles striking the surface that actually adhere. The function c represents the concentration of airborne organisms (organisms/cu ft)

in a given environment such as a Class 100 clean room.

The personnel fallout rate is a function of the number of people in the area and their shedding characteristics, as well as the surface adhesion characteristics of the deposited organisms and the positioning of the equipment. It is assumed that the personnel fallout rate is the product of a surface retention factor, g; fallout velocity of airborne particles (organisms), f_i; the personnel airborne contamination density per man, λ; and the number of men working within five feet of the surface Q. The introduction of two variables, Q and λ, was necessary to reflect the fact that the burden contribution by a worker depends both on how much he sheds and how close he is. The same model is used to predict the burden increments that result from the proximity of contaminated tools or equipment activity.

Thus, the contamination increase attributed to personnel and/or equipment fallout is given by the expression:

$$f_i g \lambda Q.$$

A change in notation and inclusion of the area of the surface gives the following formula for the effects of fallout from environment, equipment, and personnel:

$$B' = Be^{-t/v} + AvR(1-e^{-t/v}) \qquad \text{(Equation 2)}$$

where $\quad R = f_i \, g(c + \lambda Q) \qquad \text{(Equation 3)}$

B' is the resulting burden (organisms),

B is the initial burden (organisms),

$e = 2.71828...$,

t is the time for the operation (hr)

v is the "average lifetime" (hr)

A is the area of the surface (sq ft),

R is the fallout rate $\dfrac{\text{organisms}}{\text{sq ft-hr}}$

f_i is the fallout velocity (ft/hr)

$\quad$ (f_1 for the horizontal surfaces f_2 for other surface attitudes),

g is the surface retention factor (dimensionless),

c is the environmental airborne concentration (organisms/cu ft),

Q is the number of men working within five feet of the surface,

λ is the personnel airborne contamination (organisms/cu ft-man).

The quantities B', B, t, v, c, and Q are represented by histograms in the burden prediction model.

b. Contact

Normal physical contact is sufficient to remove (or deposit) organisms from the surface of a spacecraft part. The number of organisms transferred will depend on the total area contacted, a, of the surface and the tool or hand. In addition, the retention factor ("stickiness") of the surface, S_1, and of the tool or hand, S_2, plus the microbial concentration b_t of the tool or hand all contribute to the contamination of a contacted part.

Consider Figure 4. Let t denote a tool or hand, and p a part with area A and microbial burden B. Define n_{tp} to be the number of organisms transferred from t to p and n_{pt} to be the number of organisms transferred from p to t.
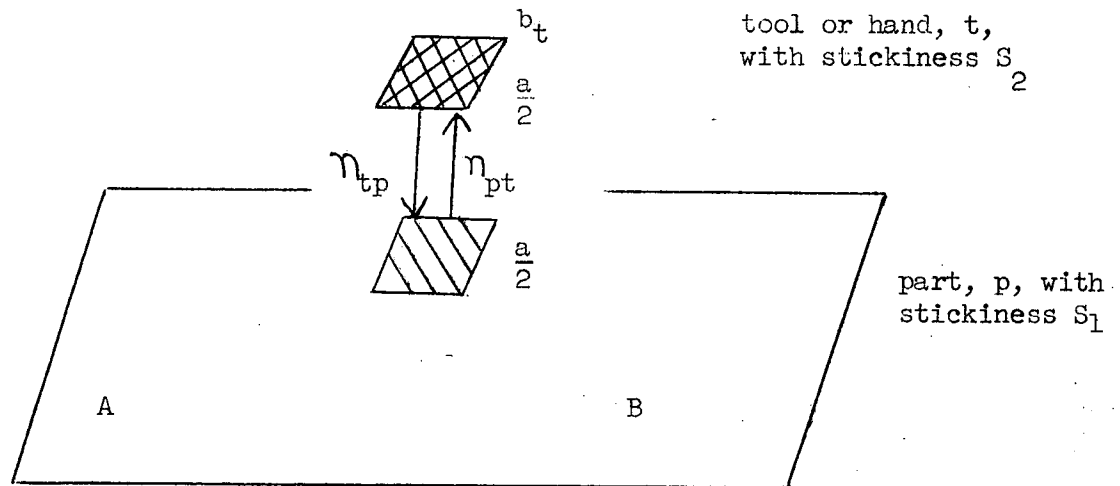
Fig. 4 Burden Transfer by Contact

The new burden, B', on the part resulting from contact is then

given by B' = B + n_{tp} - n_{pt} is a function of B, A, a, and S_1:

n_{tp} = $\frac{B}{A}$ · $\frac{a}{2}$ S_1; and n_{tp} is a function of b_t, a, and S_2: n_{pt} =

b_t · $\frac{a}{2}$ · S_2 Substituting for n_{tp} and n_{pt} in the original equation

for burden transfer due to contact we get the equation used in the

MBPM:

$$B' = B\left(1-\frac{aS_2}{2A}\right) + \frac{b_t a\ S_1}{2}, \qquad \text{(Equation 4)}$$

Where:

B' is the final burden on the surface (organisms),

B is the initial burden on the surface (organisms),

a is the total area contacted of the surface and tool or hand (sq ft),

S_1 is the retention factor of the surface (dimensionless),

A is the area of the surface (sq ft),

S_2 is the retention factor of the tool or hand (dimensionless, and

b_t is the microbial concentration on the tool or hand ($\frac{organisms}{sq\ ft}$).

The factors S_1 and S_2 for various materials range from zero for

nonsticky surfaces to one for surfaces with complete retention.

c. Decontamination

In order to account for the effects of washing, wiping, vacuum

cleaning, etc, the linear expression specifying a removal fraction

k was assumed:

$$B' = B\ (1 - k), \qquad \text{(Equation 5)}$$

Where   B' is the resulting burden (organisms),

B is the initial burden (organisms),

k is the removal (kill) factor (dimensionless), $0 \leq K \leq 1$.

C. Random Variable Combining Method

The expressions discussed in II. B include parameters which can be considered random variates, or more precisely each expression is a random variable that has been defined as a function of one or more other random variables. Consequently, early in the evolution of the MBPM, it was necessary to choose a method for combining random variables within a given expression as well as combining the resultants. Several methods were available for implementing these calculations, such as (a) obtaining closed-form solutions, (b) using Monte Carlo simulation, (c) deriving expected values, or (d) combining histograms. There are varying degrees of mathematical and computational difficulty with each of these methods (Ref.10).

The closed form solution requires that the probability density functions representing the random variables be described in closed mathematical form. The data from which these density functions are derived rarely lend themselves to a closed form mathematical description. However, some density functions may be described in this form either directly or through curve fitting. Even when all of the density functions of interest are known in closed mathematical form, it is generally not possible to perform the necessary mathematical integrations in order to arrive at a closed form solution of the problem of interest. This difficulty becomes greatly magnified when the density functions must be combined according to some complex equation.

The Monte Carlo simulation is conceptually a very simple technique in terms of formulating the problem. It consists, essentially, of randomly selecting a value from each density function, operating on the set values

in the appropriate manner (i.e., summation, multiplication, division or by some complex equation), and then repeating this process a sufficient number of times until the true density solution has been closely simulated. The shortcoming of this approach is that, when a large number of random variables is involved, the number of samples required by the Monte Carlo approach to simulate the true answer is extremely large, thus requiring a large amount of high speed computer time.

The expected value approach requires the calculation of the arithmetic mean for each of the parameters, substituting into the appropriate equation, evaluating, and then repeating this process as a function of time. The shortcoming of this approach is that with spacecraft and environmental microbiological data the arithmetic mean is an unstable estimator (Ref. 11). Consequently, there would be difficulty in drawing conclusions from the results.

The histogram combining method is a straight forward numerical technique for performing arithmetic operations of addition, multiplication and division. The histogram method has the following advantages: (1) accounts for un-certainities in input parameters by representing the random variables as discrete probability density functions (pdf), (2) performs the calculations using a relatively small amount of high speed computer time. A difficulty is that the result and the interpretation of the statistical limits is not mathematically rigorous. (This will be discussed in Section IV.)

The basis for the histogram operations of adding, multiplying and dividing are described in Appendix B.

III. COMPUTER PROGRAM MACROLOGIC

A. Description

In order to provide flexibility and ease of use, the MBPM has been written as three separate routines, which may be exercised together or independently by one main calling routine. The three routines are the Input Translator Program (ITP), the tape alteration subroutine (TAS), and the Burden Prediction Subroutine (BPS). MBPM organization is shown in Figure 5.

The ITP allows the user to account for all operations on a one-to-one basis, i.e., information can be provided describing the operation and length of time if required in a particular environment, parts affected, number of men near the spacecraft, and the tools they used and clothes they wore. Output from the ITP is on a magnetic tape to be used as input to the TAS.

The TAS, with output data from the ITP and possible changes or additions, performs the function of preparing a tape suitable for input to the BPS.

The TAS output data tape is then read by the BPS, where all burden predictions are made and printout directed.

The three programs may be used in combination or separately. For example, it may be desirable to first exercise the ITP only for an emulation in order to eliminate coding input errors. Then, with a valid ITP output tape the TAS and BPS can be run together to obtain the burdens for each day of the emulation. Later, it may be desirable to change the TAS data tape and to obtain a new burden prediction (e.g., for a sensitivity study - see glossary). A more detailed discussion of these concepts is given in the Microbial Burden Prediction Model User's Manual.

```
┌─────────────────────────────────────────────────────────────────────────┐
│                                                                           │
│   ┌──────────┐   ┌──────────┐   ┌──────────┐                              │
│   │  INPUT   │   │   TAPE   │   │  BURDEN  │                              │
│──▶│TRANSLATION│─▶│ALTERATION│─▶│PREDICTION│──▶                          │
│   │ PROGRAM  │   │SUBROUTINE│   │SUBROUTINE│                              │
│   └──────────┘   └──────────┘   └──────────┘                              │
│                                                                           │
│                              MBPM                                         │
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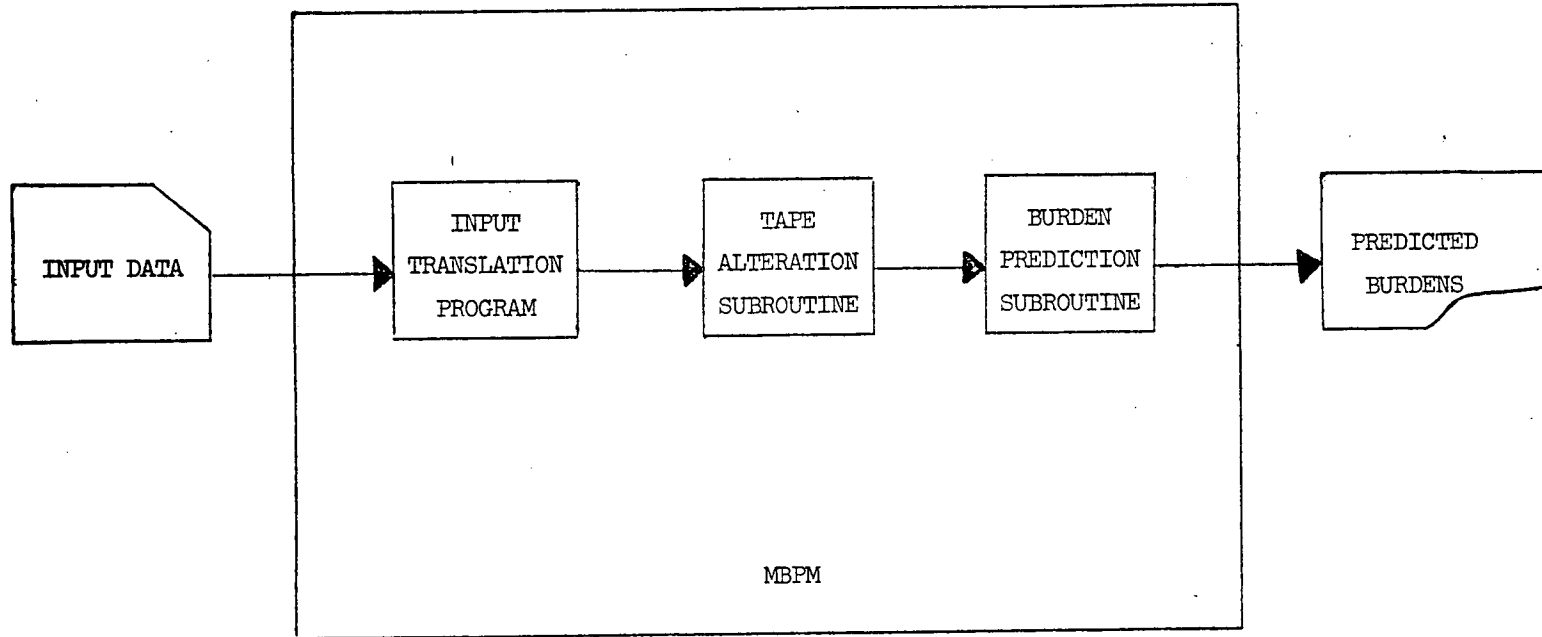
INPUT DATA

PREDICTED BURDENS

Figure 5.   Microbial Burden Prediction Model Organization

B. Method for Facilitating Input Preparation

Experience gained from the preparation of input data during early program
usage indicated the desirability for a more manageable method of preparing this
data. The input translator program (ITP) was developed to meet this need
(Table 3). The macrologic for the ITP is given in Figure 6.

The ITP performs much of the repetitious and time-consuming work involved
in preparing input data, and was programmed so that only minor revisions had to be
made to previously developed portions of the program. In most cases a mistake in
the input data to the ITP is printed as an error, but does not stop the production
of an input tape for the tape alteration subroutine (TAS).

The manual preparation of input data is therefore reduced to coding the
Quality Assurance Daily Activity Log, keypunching this information, and making
corrections to any errors which are flagged by the ITP. A flow diagram of this
procedure is shown in Figure 7.

Data is input on four types of cards (Stage, Task, Subtask, Parts) to account
for all of the operations indicated on the QA Daily Activity Report during the
assembly, test, and checkout of a spacecraft. The stage and task cards were
described in the previous section, and are detailed in the User's Manual.

The subtask is the basic unit of the program, and the subtask card accounts
for time, men, environment, tools, operations, and parts necessary for one step
in the spacecraft assembly and test sequence. Associated with each subtask card
is a parts card identifying the spacecraft part of parts affected during that sub-
task. An example of the ITP coding done for these two cards is shown in Table 4.
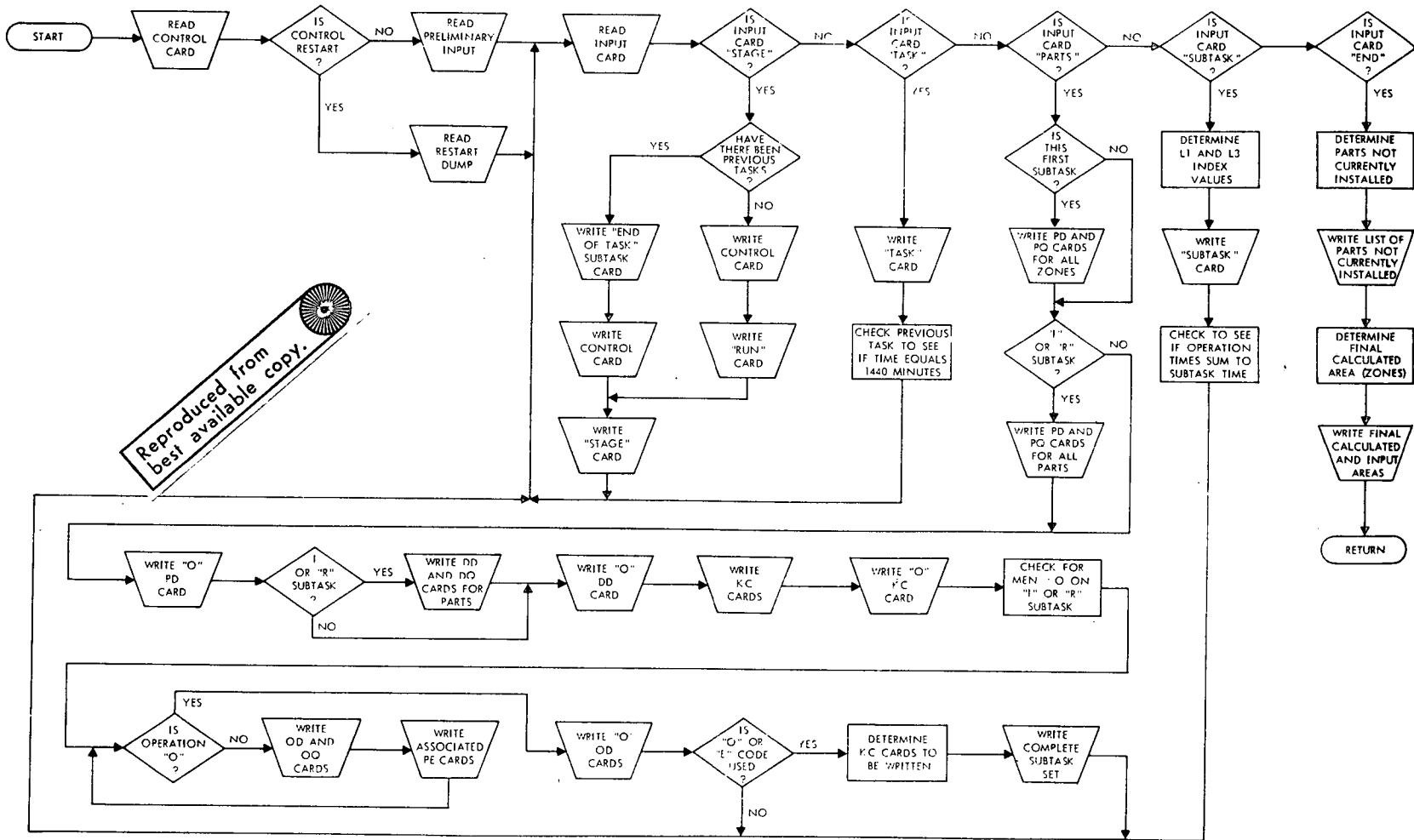
START → READ CONTROL CARD → IS CONTROL RESTART ? — NO → READ PRELIMINARY INPUT → READ INPUT CARD → IS INPUT CARD "STAGE" ? — NO → IS INPUT CARD "TASK" ? — NO → IS INPUT CARD "PARTS" ? — NO → IS INPUT CARD "SUBTASK" ? → IS INPUT CARD "END" ?

IS CONTROL RESTART ? — YES → READ RESTART DUMP

IS INPUT CARD "STAGE" ? — YES → HAVE THERE BEEN PREVIOUS TASKS ?
HAVE THERE BEEN PREVIOUS TASKS ? — YES → WRITE "END OF TASK" SUBTASK CARD → WRITE CONTROL CARD → WRITE "STAGE" CARD
HAVE THERE BEEN PREVIOUS TASKS ? — NO → WRITE CONTROL CARD → WRITE "RUN" CARD

IS INPUT CARD "TASK" ? — YES → WRITE "TASK" CARD → CHECK PREVIOUS TASK TO SEE IF TIME EQUALS 1440 MINUTES

IS INPUT CARD "PARTS" ? — YES → IS THIS FIRST SUBTASK ?
IS THIS FIRST SUBTASK ? — YES → WRITE PD AND PQ CARDS FOR ALL ZONES
IS THIS FIRST SUBTASK ? — NO → OR "R" SUBTASK ?
"I" OR "R" SUBTASK ? — NO (→ up)
"I" OR "R" SUBTASK ? — YES → WRITE PD AND PQ CARDS FOR ALL PARTS

IS INPUT CARD "SUBTASK" ? — YES → DETERMINE L1 AND L3 INDEX VALUES → WRITE "SUBTASK" CARD → CHECK TO SEE IF OPERATION TIMES SUM TO SUBTASK TIME

IS INPUT CARD "END" ? — YES → DETERMINE PARTS NOT CURRENTLY INSTALLED → WRITE LIST OF PARTS NOT CURRENTLY INSTALLED → DETERMINE FINAL CALCULATED AREA (ZONES) → WRITE FINAL CALCULATED AND INPUT AREAS → RETURN

WRITE "O" PD CARD → OR "R" SUBTASK ? — YES → WRITE DD AND DQ CARDS FOR PARTS → WRITE "O" DD CARD → WRITE KC CARDS → WRITE "O" KC CARD → CHECK FOR MEN·O ON "I" OR "R" SUBTASK
OR "R" SUBTASK ? — NO

IS OPERATION "O" ? — YES
IS OPERATION "O" ? — NO → WRITE OD AND OQ CARDS → WRITE ASSOCIATED PE CARDS → WRITE "O" OD CARDS → IS "O" OR "E" CODE USED ? — YES → DETERMINE KC CARDS TO BE WRITTEN → WRITE COMPLETE SUBTASK SET
IS "O" OR "E" CODE USED ? — NO

Figure 6. Input Translator Program Macrologic

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```
┌──────────────┐     ┌──────────┐     ┌──────────┐     ┌──────────┐     ┌──────────────┐
│   VISUAL     │     │    QA    │     │  CODING  │     │ KEYPUNCH │     │   INITIAL    │
│  MONITORING  │ ──► │   LOG    │ ──► │          │ ──► │          │ ──► │   ITP RUN    │
└──────────────┘     └──────────┘     └──────────┘     └──────────┘     └──────────────┘
```

CODING
- INTERPRET
  LOG
- TRANSFORM
  LOG

KEYPUNCH
- CHECK
  CODING

INITIAL ITP RUN
- PREPARE ITP
  DETAILED INPUT
  INFORMATION

CORRECT
ERRORS

PREDICTED
BURDENS   ◄──   BPS RUN   ◄──   TAS RUN

TAS RUN
- PREPARE
  TAS INPUTS
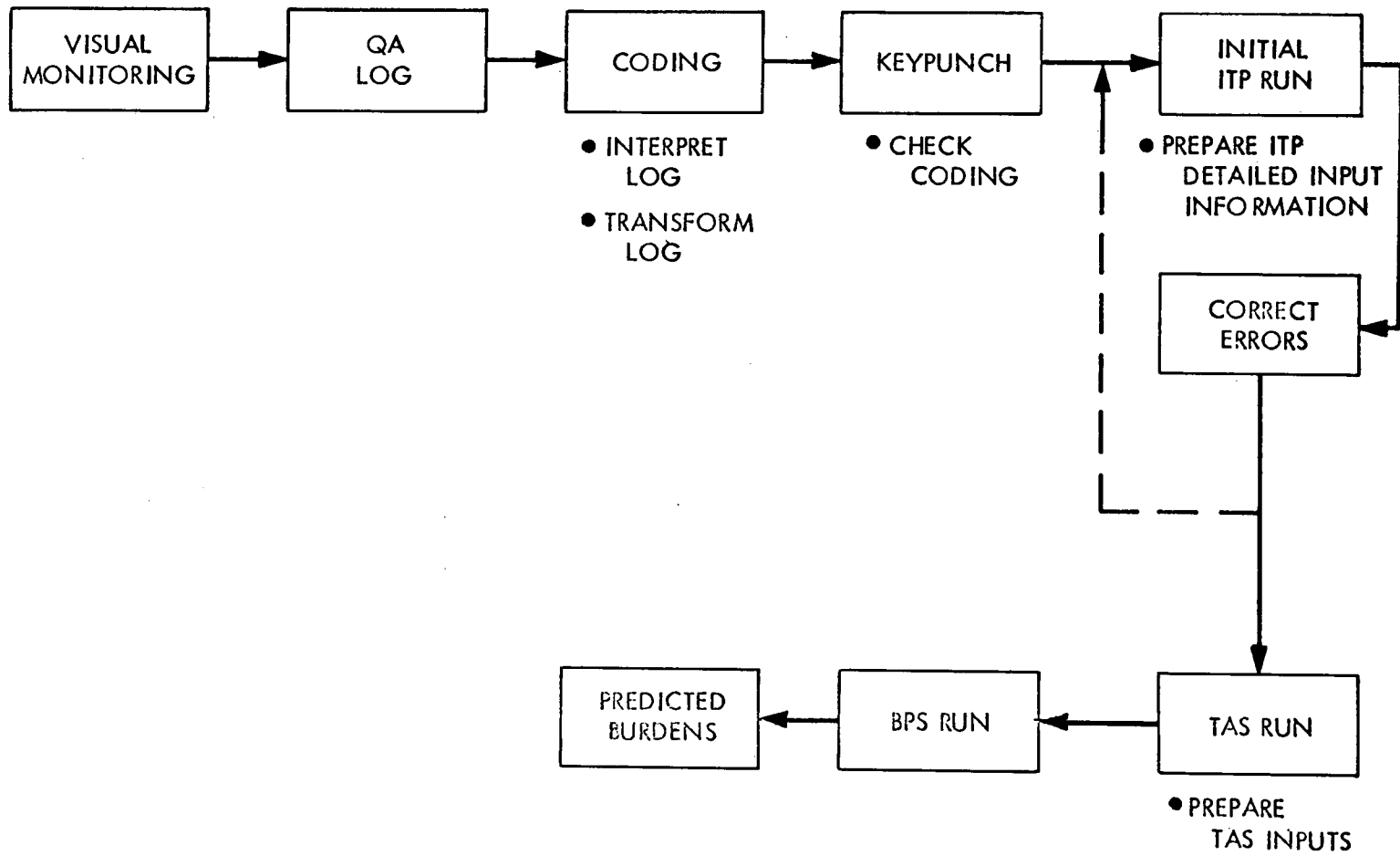
Figure 7. Spacecraft Emulation Preparation Procedure

Table 3. Example of ITP Subtask and Parts Cards

Table 3. Example of ITP Subtask and Parts Cards

SUB-TASK	01	INSTALL UPPER RING HARN	510	2H1	1	1	400	2	4014	70
PARTS	01A02	15A01X15A02X								
	02REM	FASTENERS RING HARN	195	2H1	R	2	95	1 100		
	01A02	15A01X15A02X								
	03SEC	IN HIGH BAY	1440	H1	T	18	1440			
	00000									

900-566

In theory, the manual involvement with the data ends here. If the cards are in the proper sequence, the ITP will run and produce a tape that is acceptable to the MBPM. In practice, however, the printout of the ITP should be examined for errors, as the ITP will take corrective action to prevent termination of the computer run. These errors may be in any of the following categories: (1) errors of omission in the format, which in fact are not errors (for example, an operation time so short as to be approximately zero), (2) errors that have no effect on the output (for example, two successive installations of the same part; the program ignores the second installation), (3) errors that have a small effect on the output (for example, if no men are specified for an installation operation, the ITP will assume that one man was involved, whereas, there could have been several), and (4) errors that might have considerable effect on the output (for example, a part with a large area (and probably large burden could have been removed and not reinstalled before launch).

The ITP has a restart capability, meaning that (new) data from cards can be combined with a previously written restart tape in order to obtain an updated burden. Using restart tapes new data can be input in near realtime instead of inputting the entire card deck each time new data is keypunched.

C. Required Input Histograms

In addition to spacecraft assembly data, specified values and histograms must be initially input to the ITP. Certain histograms are also necessary on the first computer run through the TAS.

For the ITP, a spacecraft parts list showing the area of each part is input first. Next come two histograms giving information about the top exposed and other exposed areas of the parts. Followed by these are constants specifying data indigenous to the emulation being performed, a card specifying decontamination.

operations, and finally a card describing the environments encountered in the emulation.

For the TAS, histograms must be input for each of the environments, as well as data specifying the operations and histograms describing the model histogram and other factors present in the emulation (e.g. average lifetime, S_1, S_2, B_t). Details for inputting the histograms into the computer program are discussed in the Users Manual. The basis for the histograms used in the Mariner '71 emulation are given in Appendix C.

IV. INTERPRETATION OF BURDEN PREDICTION RESULTS

The computer model produces a microbial burden prediction in the form of a histogram with probability P_i assigned to each interval (x_{i-1}, x_1); a typical burden histogram is portrayed in Figure 8.
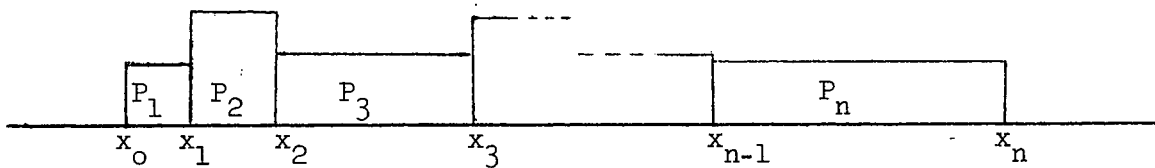
Figure 8. Typical Burden Histogram

For example, with reference to Figure 8 the probability p_1 assigned to the interval (x_o, x_1) is represented by the height (ordinate value) of the block between x_o and x_1.

The resultant histogram should be interpreted as a computed measure of belief concerning the magnitude of the burden, with odds read directly from the histogram itself. (Ref. 4)

"The output histogram must be interpreted as an (a posteriori) distribution of a parameter, given (a priori) distributions on the many input parameters and a given complex function for combining those input parameters. One would simply take the 5th percentile and 95th percentile of the output histogram, and call this a 90% "credible" interval for the burden. It would be interpreted as a betting statement in the sense that one would bet 9:1 the true burden is in that interval, or 1:9 that it is not, and be indifferent about which sides one takes." (Ref.4)

A.   Output Accuracy

In a given application, the correspondence between the model prediction and the actual microbial burden is affected by the accuracy of the burden prediction formulas, the accuracy of the input data, and the accuracy of the calculations in the computer.

The burden prediction formulas, one for contact and one for fallout, were chosen to provide a good fit with the experimental data available.

However, even if the exact formulas were used the output would be worthless unless the inputs were accurate. Realizing the importance of this accuracy JPL implemented a carefully planned methodology for obtaining data from prescribed sites on spacecraft parts and in the assembly environment. All procedures were carefully documented and the data input to a bioburden storage and retrieval computer program. The data for aerobic vegetative organisms and spores were used to form initial burden histograms, based on a logarithmic scale, for the parts and environments. A detailed description of the construction of these histograms is given in Appendix C.

Because of uncertainties in interpreting the extreme percentiles of output burden histograms, a detailed analytical study was made of histogram combining

processes and results incorporated into the MBPM (Ref 13, Chapter II, C).

With these three considerations, experimentally determined formulas, good input data, and improved confidence in the internal computer calculations, predicted burdens appear to compare favorably with those obtained from direct assays.

B. Model Verification

Examination of the emulations of the Mariner '67, Mariner '69 and Mariner '71 indicates similarity among predicted burdens. Figures 9, 10, and 11 present the mean burdens for each of these emulations. It should be noted that whereas the bases for determination of the values of certain input parameters differed to show independence among emulations (e.g., in the evaluation of environments some of those for the M '67 were based on engineering judgment and those for the M '71 based on fallout strip data), the predicted results are similar. In addition, it can be seen that bioassay estimates follow the same pattern as predictions.

It is felt that the explicit procedures, analytical methods, and detailed documentation that resulted from this study have advanced planetary quarantine technology and its effective application to flight projects.

C. Sensitivity Analysis

A series of computer runs were performed to determine the increase in predicted burdens when selected input parameters were increased by a factor of 10 (an order of magnitude). Runs on the MM '67 and MM '71 emulations with the same parameters increased by an order of magnitude indicated a consistency in burden changes. The following parameters, in respective order, were observed to be the most important input parameters in affecting a change in the predicted burden
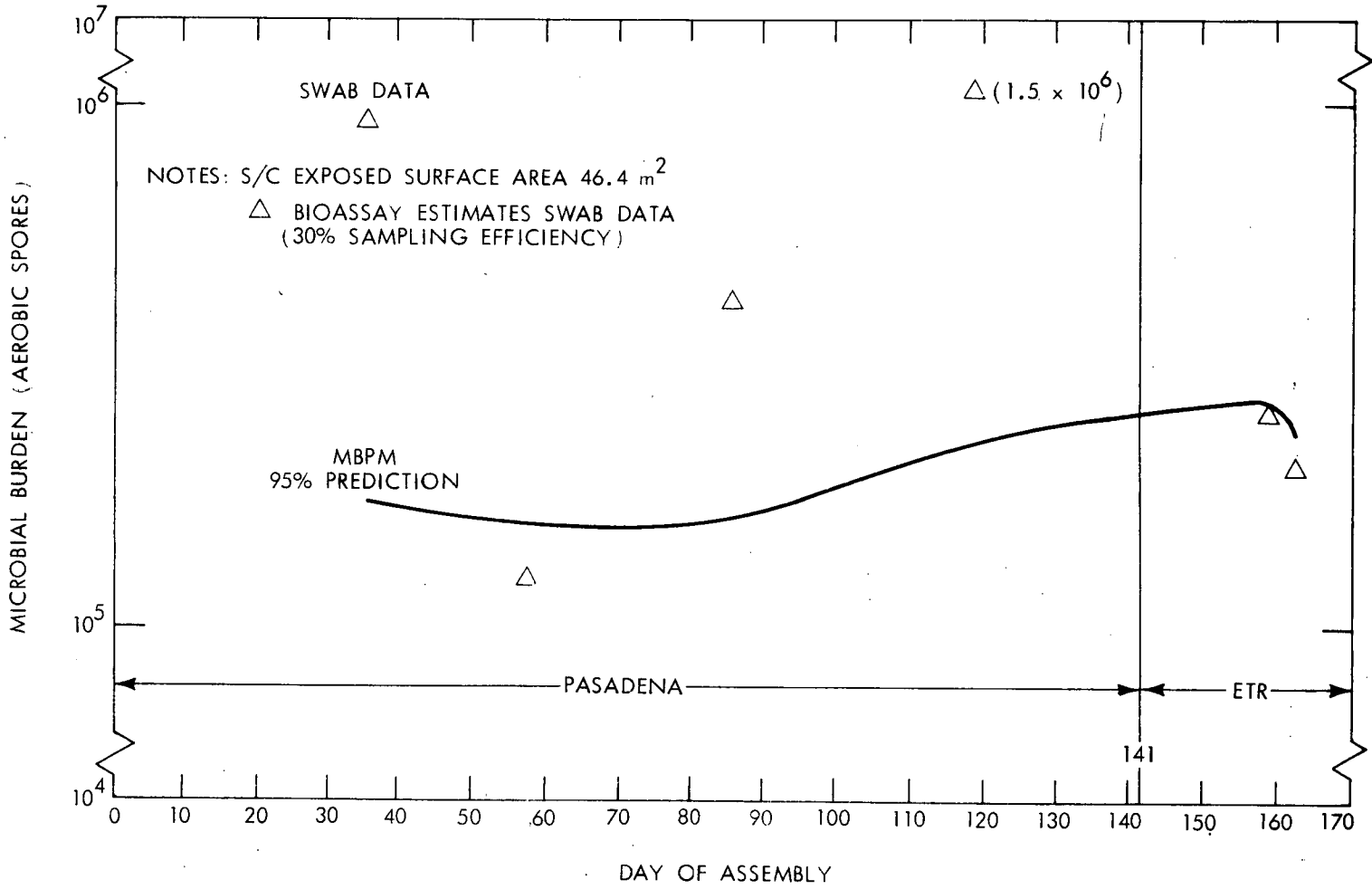
Figure 9. Comparison Between Estimates and Prediction — Aerobic
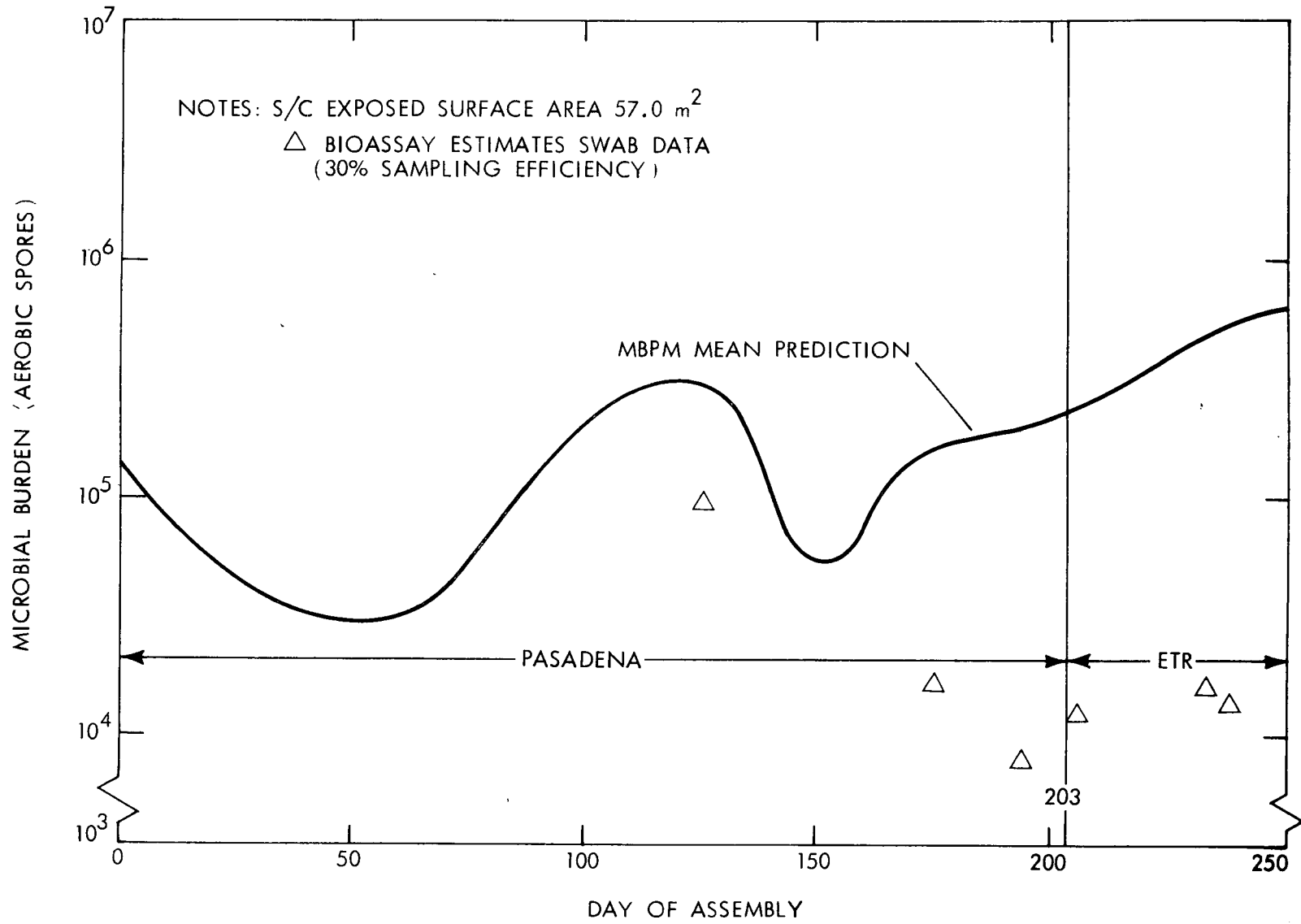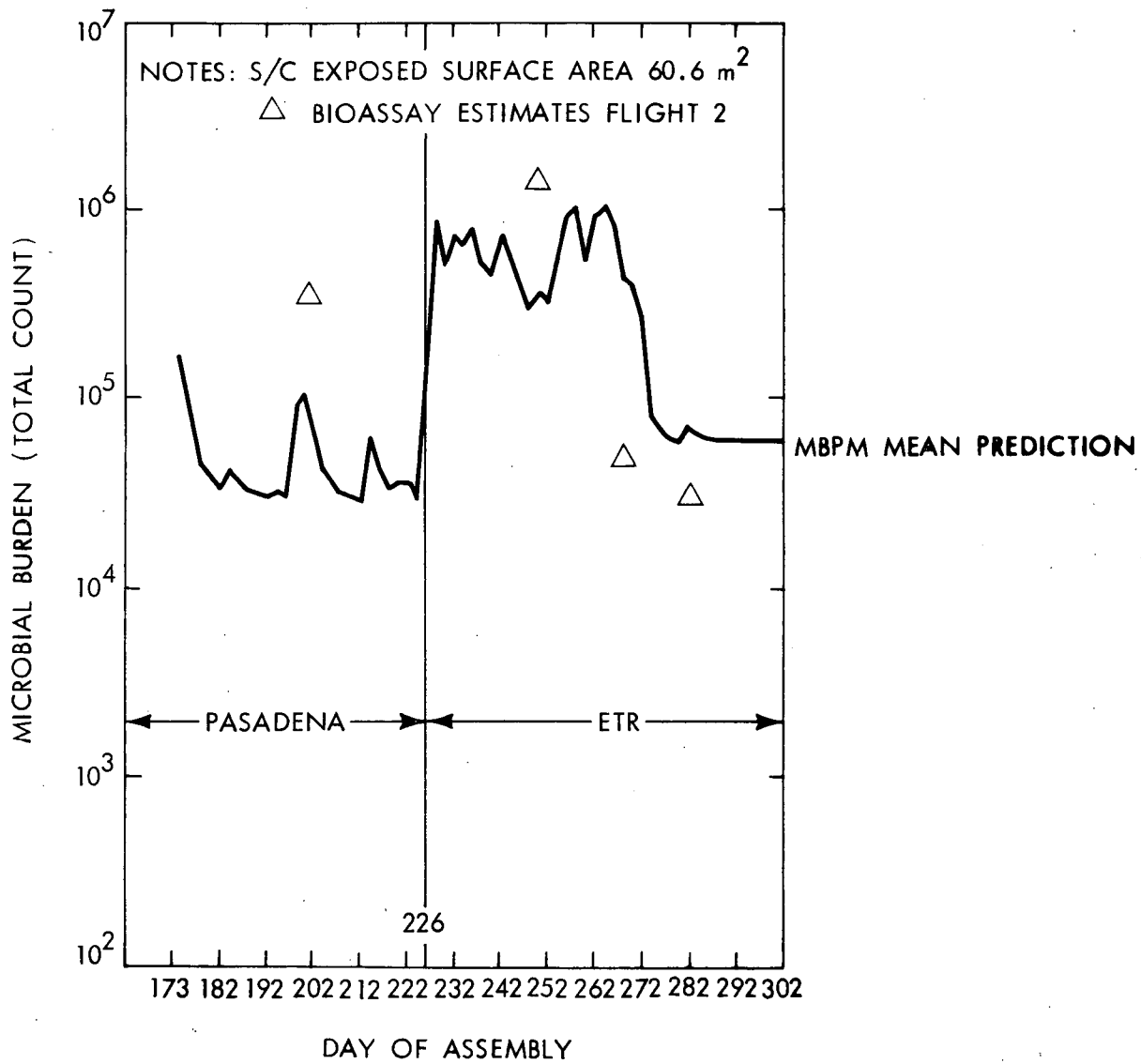Spores — Mariner '67

Figure 10. Comparison Between Estimates and Prediction — Aerobic
Spores — Mariner '69

Figure 11. Comparison Between Estimates and Prediction — Total Count — Mariner '71-2

1. Average lifetime of an organism

2. Environmental fallout at the Eastern Test Range

A detailed presentation of sensitivity studies is given in Appendix E.

V. POSSIBLE APPLICATIONS

A. Spacecraft

The microbial burden prediction model has been designed with sufficient versatility so that it can be applied to three different phases of an on-going flight program. The three phases include: 1) planning, 2) assembly and test, and 3) immediate prelaunch.

For the planning phase, the microbial burden prediction model can serve as a management tool to facilitate decisions concerning precautionary measures to be incorporated when the hardware is assembled and tested. Also, prior to the initiation of actual buildup, alternate flow sequences could be examined to determine an optimum sequencing for minimizing the accumulation of burden on the hardware. For example, if a chemical cleaning of a given piece of hardware is warranted, the model can assist management in determining the appropriate point in the sequence when the cleaning operation should be performed. The MBPM could be very useful in the decision making process for determining what level of cleanroom facilities should be used for the assembly and test of the spacecraft. During the spacecraft buildup and checkout phase, the MBPM can be used to detect unintended departures from planned rates of bioload accumulation. The model could be used in the following manner: on a weekly (daily or monthly) basis the model is exercised using information regarding the assembly activity of the preceding days; the resultant microbial burden prediction is compared to that expected from the planned sequence at the same point in time. If the predicted burden level is significantly higher

then the planned, e.g. an order of magnitude, project management would be alerted, and corrective action initiated.

During the immediate prelaunch phase, the predictions from the MBPM would be used to determine the microbial loading on a planetary landing spacecraft immediately prior to subjecting the lander to the terminal sterilization cycle. For non-landing hardware, such as orbiters or flybys, the predictions from the MBPM could be used for part of the justification for certifying the planetary quarantine acceptability of the spacecraft and for the post launch planetary quarantine analysis.

B.   Civil Systems Applications

The basic logic of the model is such that it is versatile and applicable to many types of sequential flow processes, such as stream pollution or food processing. Examples of potential civil systems applications are given below.

A possible application for stream pollution could be for the purpose of evaluating the potential effectiveness of proposed control measures. The MBPM could be modified to simulate oxidation, sedimentation, and other processes occurring in a stream system and to predict the concentration of various pollutants at selected points of the stream. The analogy between spacecraft buildup and test networks and stream networks is given in Table 4.

A potential application in the food processing industry is to standardize the inspection of processing plants. A baseline acceptance criteria could be established for a given food product line based on experience and historical information regarding various environments and activities that are involved. An inspector could go into a plant, fill out a given form concerned with the product flow and input this into the computer. The computer program would 1) construct a food process flow, 2) compare it to the baseline acceptance criteria and 3) rate the

processing plant with other plants processing similar foodstuffs. This approach could minimize inspector variations (i.e. human judgment factors) in the government inspection effort.

VI. SUMMARY AND CONCLUSIONS

The purpose of this study was to develop a computer program for predicting microbial burden on an unmanned planetary spacecraft. The prediction model is intended to be used as an analytical tool for supplementing the biological assays of a spacecraft by simulating the microbial accretion during periods when assays are not taken, reducing the number of microbiological assays that are required, and predicting the microbial loading on a lander immediately prior to sterilization and other non-lander equipment prior to launch. The microbial burden prediction model (MBPM) has several significant features:

Flexibility - it can be used to simulate the assembly and test of any type of spacecraft, manned or unmanned, or any part thereof.

Analysis of Operations - the MBPM provides the capability to analyze assembly and test operations in terms of discrete, repetitive procedural steps for the purpose of identifying significant microbial accumulation events.

Versatility - the MBPM can be used before, during, or after the actual assembly is performed. As such it can serve as a planning tool, control tool, or post launch analysis tool, respectively.

Histogram Combining Method - the MBPM uses a unique random variable combining method which accounts for uncertainties in input parameters by representing the random variables as discrete probability density functions and performs the calculations using a relatively small amount of high speed computer time.

To verify and validate the MBPM, prediction results were compared to estimates derived from the direct assays. As noted in Section IV, there was good agreement. The microbial burden prediction model can be applied not only as a prediction instrument by the planetary quarantine engineers but also as project management and control tool during an on-going spacecraft program.

Lastly, the basic logic of the model is such that it has potential applicability to many other types of sequential flow processes, such as stream pollution or food processing.

Table 4. Microbial·Burden-Steam
Polution Analogy

DESCRIPTION OF INPUT IN MICROBIAL BURDEN MODEL	ANALOGOUS DESCRIPTION IN STREAM POLLUTION MODEL
ZONES, SUBZONES, PARTS	RIVERS, STREAMS, CONSTITUANTS
SURFACES	POLLUTANTS
SURFACE AREA	FLOW RATE
ASSEMBLY AND TEST ACTIVITIES (PARAMETERS ASSUMED CONSTANT DURING EACH ACTIVITY)	STREAM SECTIONS (PARAMETERS ASSUMED CONSTANT THROUGHOUT EACH SECTION)
ASSEMBLY AND TEST PARAMETERS	STREAM PARAMETERS
DURATION OF OPERATION (TIME)	TIME TO TRAVERSE STREAM SECTION
PARTS TO BE JOINED	STREAMS ENTERING MAIN STREAM
AREA CHANGES	CHANGES IN FLOW RATE
SURFACE BURDEN	POLLUTION CONCENTRATION, BOD
FALLOUT	DISTRIBUTED SOURCES OF POLLUTION
CONTACT	POINT SOURCES OF POLLUTION

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APPENDIX A

BASIC ASSUMPTIONS

Appendix A.   Basic Assumptions

This appendix contains a summary of fundamental assumptions made during the development of the microbial burden prediction model.

1. In order to simulate the plateau phenomenon observed in the experimental data, it was necessary to assume that organisms remain (alive) on a given surface a certain average length of time and then (somehow) disappear. (This assumption can be referred to as the average lifetime assumption, the half-life assumption, or the disappearance rate assumption.)

2. It is assumed that the fallout rate R is given by R = surface adherence factor x fallout velocity x concentration.

3. The fallout velocity is assumed constant in a given environment, and is otherwise assumed to be a well-defined measureable quantity.

4. The contamination increase attributed to personnel and/or equipment fallout is a linear function of the number of men, Q, within five feet of the surface (i.e. 0 to 5 ft) and the personnel airborne contamination.

5. The contact model assumes that the surface retention factors can be assigned to surfaces instead of pairs of surfaces (i.e., the interaction is negligible).

6. The computer program accounts for contact at the end of an operation even though the contact may actually have occurred at intervals throughout the operation. It is assumed that this difference is negligible. (If not, the operation can easily be separated into shorter operations.)

7. Contact is assumed to occur instantaneously.

8. The effects of decontaminating a surface (e.g. washing, wiping, or vacuum cleaning) are assumed to result in a linear reduction in burden.

APPENDIX B

HISTOGRAM OPERATIONS

Appendix B.   Histogram Operations

1. General

A histogram is a method of representing a probability density function either discrete or continuous) by grouping the portions of the distribution together into (usually equal) intervals, with the areas under the ordinate between class limits being proportional to the percentage frequendy of occurring between the class limits. For ease in representing these areas graphically, the spacing between class limits is usually a constant (Ref. 12, Chap. 2). It is not necessary to have equal spacing between class limits when treating the histogram areas mathematically, as in the Microbial Burden Prediction Model. Since the probability between adjacent class limits is represented by a constant, it is inferred that the distribution between adjacent class limits is uniform, although the data upon which the histogram is based seldom satisfy this inference. The histogram combining is based upon the assumption of a uniform distribution between adjacent class limits. Hereafter, in this report, the area between adjacent class limits will be referred to as a "bump".

The equations used in the Microbial Burden Prediction Model (MBPM), for development of the analytical expressions, (Section IIB) are as follows (underscored parameters are random variables which are represented as histograms in the computer program):

Fallout--------------------$\underline{B}' = \underline{B}e^{-t/\underline{v}} + AvR(1 - e^{-t/\underline{v}})$ Equation B-1

where $R = f_2g(\underline{c} + \underline{Q})$ Equation B-2

Contact--------------------$\underline{B}' = \underline{B}\left(1 - \dfrac{a\underline{S}_2}{2A}\right) + \dfrac{a\underline{S}_1\underline{b}t}{2}$ Equation B-3

Decontamination-----------$\underline{B}' = B(1 - k_j)$ Equation B-4

Where B' is the resulting burden (organisms),

        B is the initial burden (organisms),

        $e = 2.71828 \ldots$,

        t is the activity time (hours),

        v is the "average lifetime" (hours),

        A is the surface area (sq. ft.),

        R is the fallout rate $\left(\dfrac{\text{organisms}}{\text{sq ft-hr}}\right)$,

        f_2 is the fallout velocity (ft/hr),

        g is the surface retention factor for fallout (dimensionless),

        c is the environmental airborne contamination (organisms/cu ft),

        Q is the number of men working within five feet of the surface,

          is the personnel airborne contamination (organisms/ft 3 man),

        a is the total area of the tool and part surface contacted (sq ft),

        S_2 is the hand or tool retention factor for contact (dimensionless),

        S_1 is the hardware retention factor for contact (dimensionless),

        b_t is the contamination on hand or tool (organisms/sq ft),

        k_j is the dieoff factor (dimensionless),

        B_{n+1} is the burden after n+1 operations,

        B_n is the burden after n operations.

It can be seen by examining these four equations that the following operations involving histograms are included:

(1) Multiplying a histogram by a constant,

(2) Subtracting a histogram from a constant,

(3) Dividing a histogram by a constant,

(4) Exponentiating to a negative histogram power,

(5) Adding one histogram to another histogram,

(6) Multiplying one histogram by another histogram, and

(7) Dividing one histogram by another histogram.

The first four operations are illustrated in B-1. Figure B-1 (a) shows a histogram, H, where

$$P(x_1 \leq H < x_2) = 0.1$$

$$P(x_2 \leq H < x_3) = 0.3$$

$$P(x_3 \leq H < x_4) = 0.4$$

$$P(x_4 \leq H < x_5) = 0.2$$

x_1, x_2, x_3, x_4 and x_5 are the class limits.

Figures B-1 (b) through (e) show multiplying the histogram (pdf) by a constant c, subtracting from a constant (not necessarily the same) c, dividing by a constant c, and a constant c with a negative histogram exponent, respectively. The area of each interval is proportional to the product of the probability per unit interval (P/U), times the unit length of the abscissa between class limits. Unit interval lengths are constant (equal intervals) for (a), (b), (c), and (d). The unit interval for (e) is $c^{-x_4} - c^{-x_5}$. The value of the cumulative area of each histogram is unity and the abscissa is increasing value from left to right. No error is known to be introduced by these operations which consist of applying the operator to the abscissa without affecting the ordinate (probabilities). The mean value of the histogram is calculated by summing the area-abscissa products. For example, the mean value of the histogram in Figure B-1 is
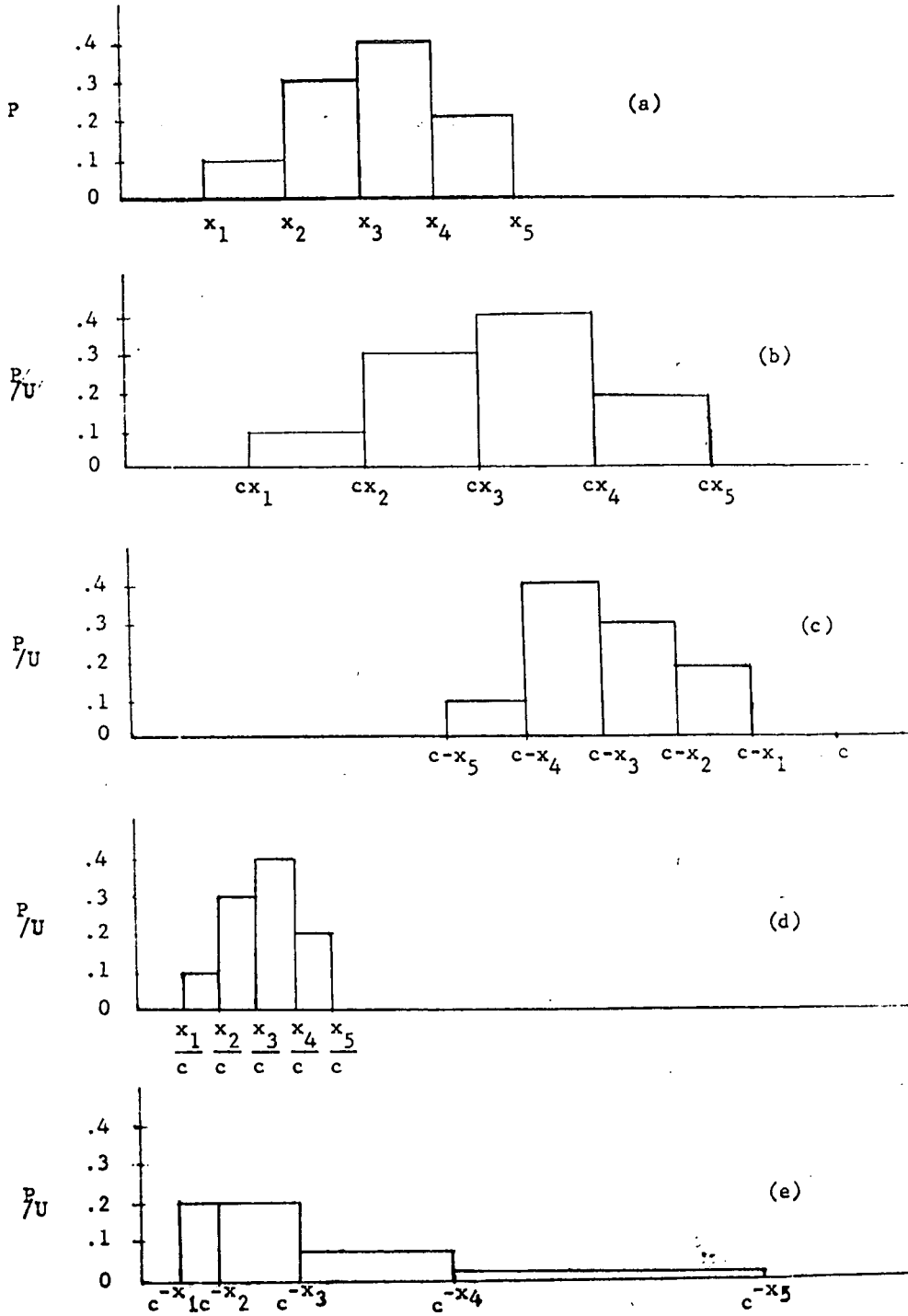
Figure B-1. Operating on Histograms with
Constants

$$H = 0.1 \quad \frac{x_2 + x_1}{2} + 0.3 \quad \frac{x_3 + x_2}{2} + 0.4 \frac{x_4 + x_3}{2} + 0.2 \quad \frac{x_5 + x_4}{2}$$

2. Addition of Histograms

Consider two independent random variables, x and y, whose distributions are represented by histograms such that

$$P(x_1 \leq x < x_2) = P_1$$

$$P(x_2 \leq x < x_3) = P_2$$
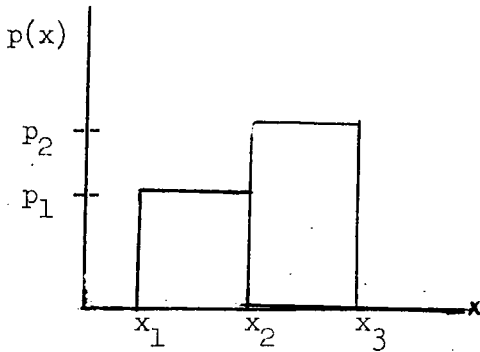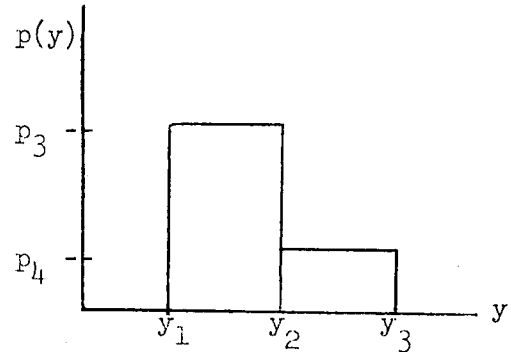
$$P(y_1 \leq y < y_2) = P_3$$

$$P(y_2 < y < y_3) = P_4$$

Figure B-2a   Addition of Histograms   Figure B-2b

The joint probabilities assuming stockastic independence are

$$P(x_1 \leq x < x_2, \; y_1 \leq y < y_2) = P_1 P_3$$

$$P(x_1 \leq x < x_2^{m} \; y_2 \leq y < y_3) = P_1 P_4$$

$$P(x_2 \leq x < x_3, \; y_2 \leq y \; 2 \; y_2) = P_2 P_3$$

$$P(x_2 < x < x_3, \; y_2 \leq y < y_3) = P_2 P_4$$

which can be shown diagrammatically as
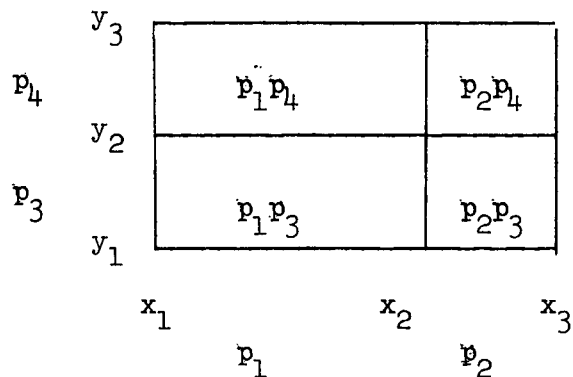
Figure B-3 "Diagram of Joint Probabilities"

Now since the distances along the axes are proportional to the values of x and y (and not their probabilities), values of constant z, where z is the sum of the two random variables, $z = x + y$, can be shown as straight lines. Any values of z can be selected. The values in the diagram are the values of z where discontinuities exist because of a change in probability, and, therefore, represent class limits on the z histogram.
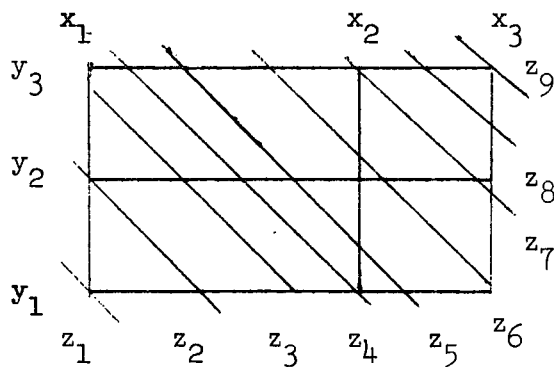

Figure B-4 "Class Limits on Resultant Histograms"

Considering the p_1p_3 block as an example, it can be seen that if x is uniformly distributed between x_1 and x_2 and if y is uniformly distributed between y_1 and y_2, then the probability p_1p_3 is uniformly distributed throughout the area, and that the probability of a portion of the area is directly proportional to the portion of the area enclosed. For example, if 1/4 the area of p_1p_3 were between z_1 and z_2, then the probability of z being between z_1 and z_2 would be $\frac{p_1p_3}{4}$. When any z area of interest crosses more than one joint probability segment, as in the case of z between z_2 and z_3, the contributions from the individual segments must be added. This is illustrated in Appendix C.1 of Ref 13.

It can be seen from the diagram above that the two-bump by two-bump addition shown results in a z histogram of eight bumps, which is the maximum for two-bump by two-bump. In the general case, where x has n - 1 bumps and y has m - 1 bumps the resulting number of bumps will be nm - 1. It is possible to have fewer than this number if a single z value goes through more than one change of probability point. Unless restricted, this progression in the number of bumps will continue with subsequent operations. In the MBPM, the number of bumps of z is made equal to the larger of the number of bumps on the input histograms by choosing the z values on the intersections as shown below. The first co-ordinate points chosen are the lower left (x_1y_1) and the upper right (x_4y_4) in the Figure B-5a. Other points are chosen by alternately moving up and right from x_1y_1 and moving down and left from x_4y_4 until the point is duplicated. In the case where n = m (Figure B-5B) when the points x_3y_2 and x_3y_3 were selected, the point half-way between would be the value on x_3, all other points being chosen as described above.
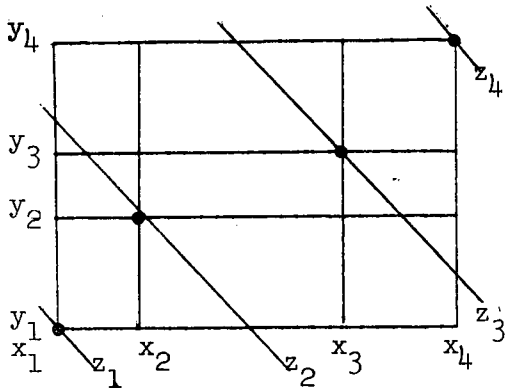
Figure B-5a
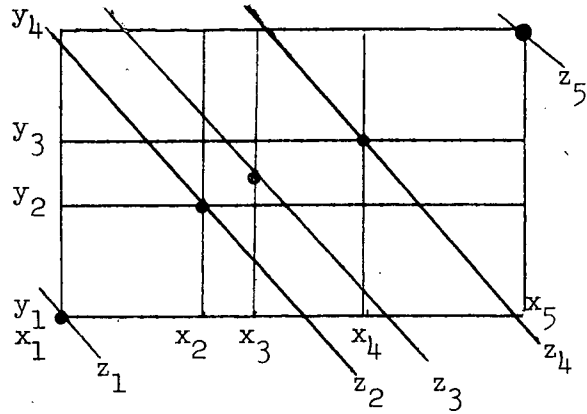Class Limit on Resultant
Histogram where $N = M$

Figure B-5b
Class Limit on Resultant
Histogram where $N \neq M$

As can be seen from the sample calculations in Appendix C.4 of Ref. 13, even though the area calculations are correct the mean is not necessarily correct. An explanation of the method of calculating the mean value of a histogram is helpful in understanding the nature of the occurrence of incorrect mean with correct areas.

The mean of a histogram can be taken as the sum of the means of the individual bumps. The mean of a bump, which is a uniform distribution, is the mean of the class limits. The mean of the variable x in the Figure B-6 would be $\bar{x} = \frac{1}{2} (x_1 + x_2)p_1 + \frac{1}{2} (x_2 + x_3)P_2$. This can be seen to be analogous to thinking of the bumps as masses of unit thickness and the mean as the location of the center of gravity. We then determine the physical moment (first statistical moment) about the axis $x = 0$, which is equal to the c.g., or mean, since $P_1 + P_2 = 1$.
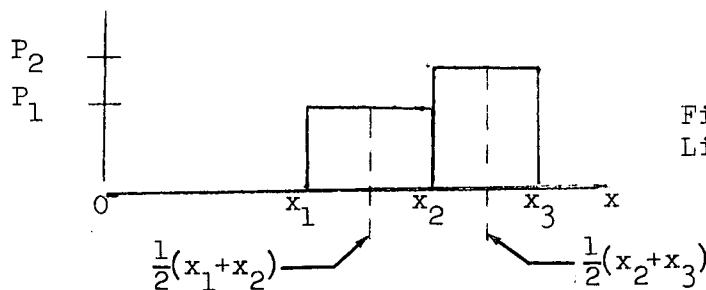

Figure B-6 Mean Class
Limits of Histograms

If the smaller values of z in the addition diagram are examined, the nature
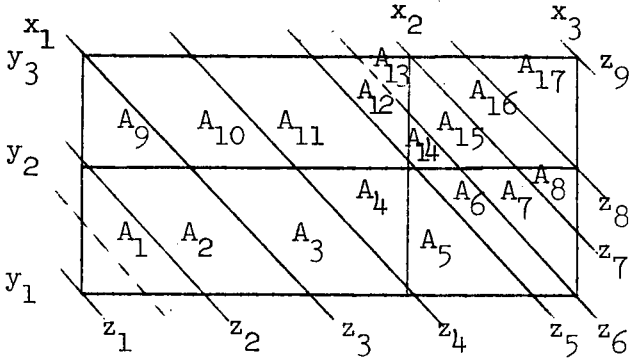
of the problem becomes apparent.

Figure B-7a
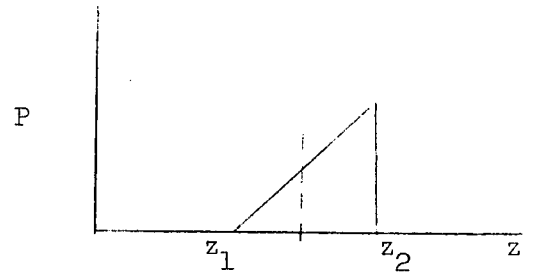Area Identification for Resultant Histograms: $N \neq m$

Figure B-7b
Area A_1 From Figure B-7a

As the dotted line moves in incremental steps from z_1 to z_2 in Figure B-7a

the area is not a constant for the steps, but increases linearly. Instead

of the distribution between z_1 and z_2 being shown as rectangle in Figure B-7b,

a triangle has been produced. Since histograms have, by definition, rectangular

bumps, the sum of two histograms is pictorially a triangle, and therefore,

not a histogram. The best that can be expected when the sum of two histograms

is represented by a histogram is the resultant will be an approximation.

By the same logic, a triangle will also be produced in the area between

z_8 and z_9. If these areas are represented in the z histogram as rectangular

bumps with the limits unchanged, the probabilities of these bumps and the

limits of the bumps are correct, but their contribution to the histogram mean

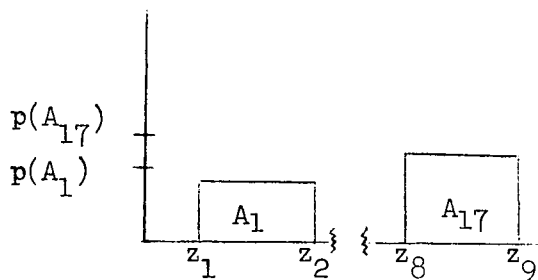is incorrect, due to the shifting of the true mean.
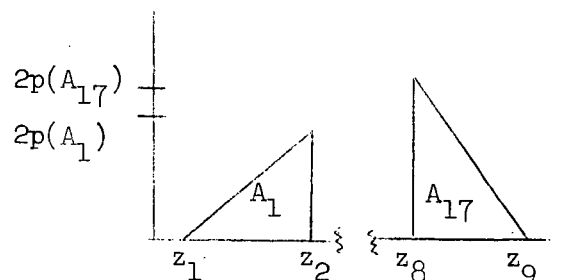

Figure B-8
Histogram of End Bumps

Figure B-9
Correct Distribution of End Bumps

Considering the base of the triangle A_1 (on the joint probability diagram) as z_2 and the base of the triangle A_{17} as z_8, the c.g. of A_1 is at $z_1 + \frac{2}{3}$ $(z_2 - z_1)$ and the c.g. of A_{17} is at $z_8 + \frac{1}{3}(z_9 - z_8)$. The histogram has the c.g. of A_1 at $z_1 + \frac{1}{2}(z_2 - z_1)$ and the c.g. of A_{17} at $z_8 + \frac{1}{2}(z_9 - z_8)$. Obviously, the triangle cannot be replaced by the rectangle and still preserve the correct area, limits, and c.g. The best approximation seems to be to preserve the area and c.g. (which contribute to the histogram mean, the best point of reference and to make any necessary adjustments on the limits. The only points which can be adjusted are the end values (z_1 and z_9) in this case, as z_2 and z_8 are common to the adjacent bumps. The area affected is also minimal, as the areas are moved from the points z_1 and z_9. The adjusted end points would then be as shown in the diagram below.
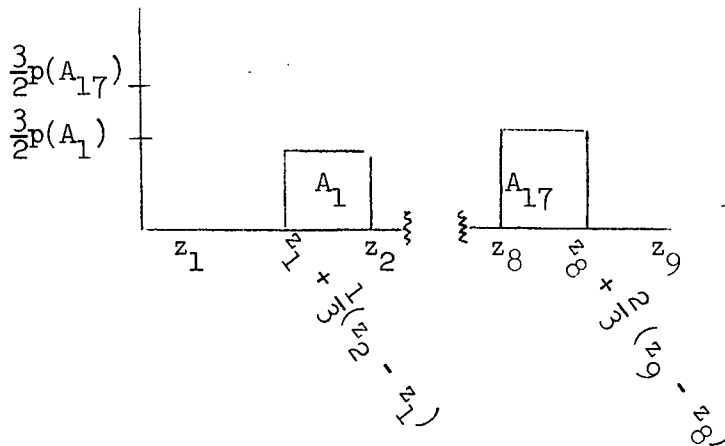

Figure B-10

Adjusted End Points of Resultant Histogram

An advantage of this method is to counteract the tendency for the end points of the histogram to spread out after repeated operations with an infinitesimal probability of being in this spread portion of the distribution.

An extension of this approach into the other bumps of the eight-bump histogram shows that triangular areas produce triangular bumps and parallelogram areas produce parallelogram bumps. Other shapes (trapezoids) can be handled as combinations of triangles and parallelograms. The resultant distribution of z is shown in the diagram below.
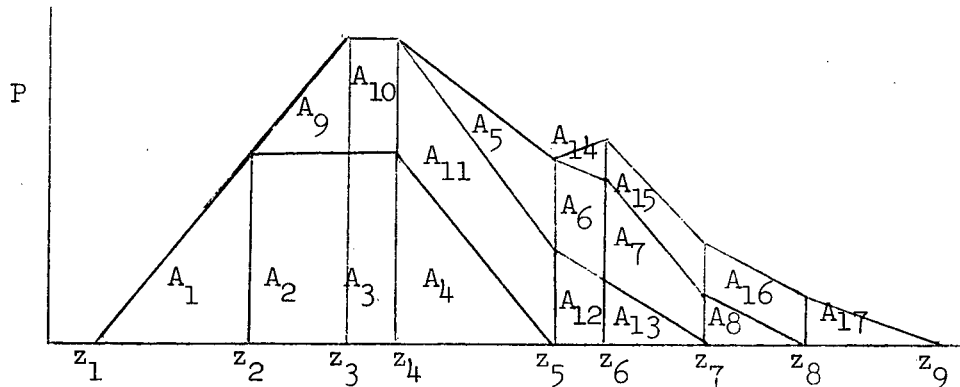

Figure B-11
Resultant Distribution of Z

This approach helps to point out another source of error. The sum of the means can be used as a check point against the mean of the sums, but is can be seen (Appendix C of Ref. 13) that these values can be in agreement and the individual bumps in error. For example, if after reducing the number of bumps, A_1 and A_4 are in the same bump, their equal and opposite errors will balance out, and the bump will be correct, but if z_4 were selected as the dividing line, between bumps, A_1 and A_4 would be in different bumps and each bump would be in error. They would not contribute to error in the histogram mean as long as they were correctly handled (as individual bumps with properly located c.g.) but would contribute when lumped with other values into a single-valued bump. The items that contribute to error in the

Figure B-11 (where z_5 is the dividing line between bumps for the resultant two-bump histogram) are A_9 and the A_{12}-A_{13} combination, and A_5 and the A_7 -A_8 combination. (See Figure B-7a.)

It should be apparent that it is impossible to represent the bumps of this figure by rectangular areas(regardless of how the bumps are combined in reducing the number) that preserve the areas, limits and means. Since the areas (probabilities) must total unity and the means are used in the only correction of accuracy, any adjustments should be done to the limits, or dividing lines between bumps. If this is done while preserving the location of the end bumps, the effect will be to skew the z distribution enough to make $\bar{z} = \bar{x} + \bar{y}$. The details of this skewing are illustrated in Appendix C.11 of Ref. 13.

This method preserves the mean value, maintains reasonable and points and distorts the shape as little as possible. (See Appendix C.10 and C.11 of Ref. 13.)

3. Multiplication of Histograms

Consider the same two variables, x and y, which were defined in paragraph 2 above. In finding the distribution of the product $z = (x)(y)$, the joint pro-babilities of x and y are the same as in addition. On a diagram similar to that used for addition, values of constant z will be hyperbolas as indicated in the figure below.
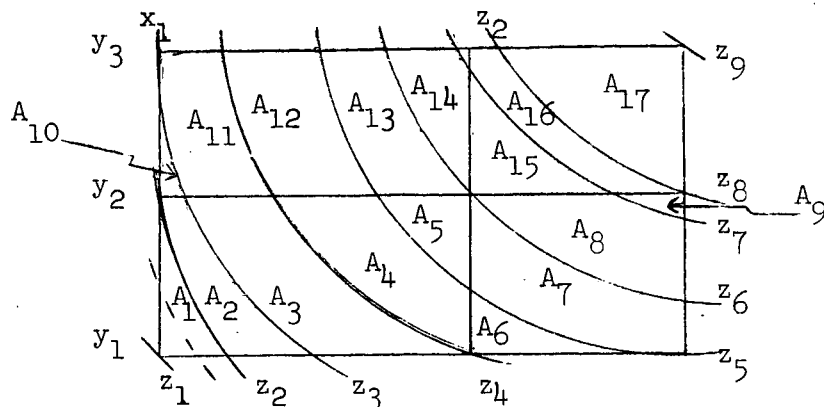

Figure B-12 "Multiplication of Histograms"

In general, the philosophy of area being proportional to probability and the manner of reducing the number of bumps after multiplication is the same as in addition. The principal difference lies in the relative difficulty of calculating areas enclosed by hyperbolas as compared to straight lines. This difference suggests an approach to use -- to approximate the hyperbolas with straight lines within an area of uniform probability.

The same approximation can be used for calculating the areas in multiplication that was used in addition, i.e., the areas between z values were taken as proportional to the differences between z values. As can be seen in the sample calculations in Appendix C, of Ref. 13, Vol X, the errors introduced by this approximation are larger, in general, when used in multiplication than when used in addition. For example, a comparison of the addition in Appendix C.4 of Ref. 13 with the multiplication of the same variables in Appendix C.9 of Ref. 13 shows an error in addition of $\frac{4.2 - 4.125}{4.2} = 1.79\%$ and an error in multiplication of $\frac{4.96 - 4.2}{4.2} = 18.1\%$.

The straight-line method, which has been incorporated into the present program for multiplication as well as for addition, decreases the error of multiplication but not to the extent that it does for addition, it eliminates the error of area calculation in addition, but only decreases the error of area calculation in multiplication. The computer run time has been increased in the same manner as in the case of addition.

As the dotted line in the preceding figure moves across A_1 with z increasing, we see that the area is a more complex function of z than it was in addition:

$$A_1 = \int_{x_1}^{z/y} \int_{y_1}^{z/x} dy\, dx = \int_{x_1}^{z/y} \left(\frac{z}{x} - y_1\right)dx \qquad \text{Equation B-5}$$

$$= z(\ln \frac{z}{y_1} - \ln x_1) - y_1 (\frac{z}{y_1} - x_1) \qquad \text{Equation B-6}$$

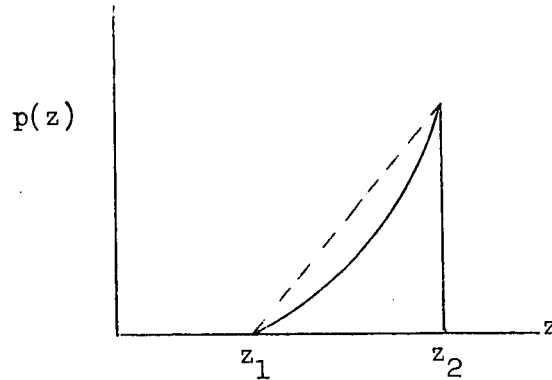When plotted as probability as a function of z, p(z) takes the form shown

below:

Figure B-13
Comparison Between p(2) and Linear Approximation

which can be approximated by the straight (dashed) line. If the straight

line is accepted as a reasonable approximation, then the method of adjusting

the end bumps that was described in parabraph 2, above can be used with

multiplication of histograms.

The fact that the product of the means is equal to the mean of the

products of two independent random variables, (Ref. 14 pp. 74) provides a

means of checking at least one value of the z histogram. Errors in multiplication

tend to be greater than in addition for the reasons already mentioned and also

because there is not the symmetry of equal triangles that tends to provide

equal and opposite errors which balance out; and errors tend to be positive

since the dashed line in the above figure includes more than the correct area.

Otherwise the same general philosophy of approximating the product of two

variables can be used as was used for approximating the sum of two variables.

The same (although probably larger) skewing effect will be exerted while

retaining the proper mean and realistic end points.

4. Subtraction of Histograms

It would seem that subtraction of histograms would be a quite simple operation, comparable to addition. Although conceptually simple, such a process contains problems of implementation. For example, in the diagram below, treated in a manner similar to addition and multiplication, negative values of $z = x - y$ are possible.
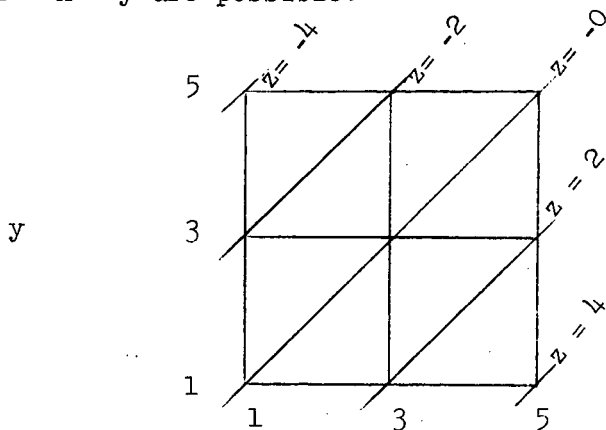
Figure B-14   Subtraction of Histograms

Negative values of burden are, of course, meaningless, and a method of addition was adopted.

In the MBPM the distribution of z is the quantity which, when added to y (which has some known distribution) will give the value x with a given distribution. A discussion of the method of subtraction as originally used in the MBPM is given in Reference 15, pp. 21-24. It may be summarized in the following diagram where x and y are the known variables, and z is the variable which is added to y to produce x in the equation $x = y + z$ (for $z = x - y$).
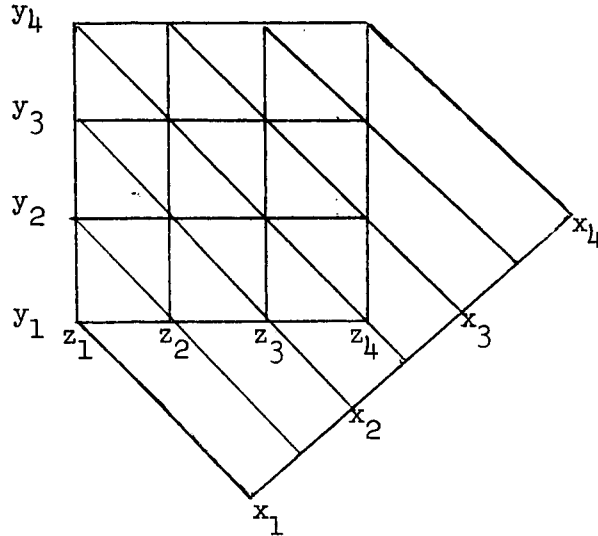
Figure B-15
Transposition of Axis for Positive Yield

There are several problems with using this method, including the following:

    (1) With some combinations of x and y it is still possible to get negative values of z;

    (2) This method requires dependence of x and y, but y and z seem to retain independence;

    (3) Not only must x and y be dependent, but they must be dependent in a manner that will give a mathematically consistent value for z;

    (4) In an example given in Reference 15, where x and y are identical, z must equal 0 with probability 1, which is difficult to justify in a real situation such as the decontamination process.

In view of these problems inherent to histogram subtraction, the place where subtraction is used in the MBPM was examined. Equation B-3, which is used to calculate the contamination caused by contact with hands or tools, was performed in the MBPM as $B' = B - \dfrac{aS_2 B}{2A} + \dfrac{aS_1 b_t}{2}$, which required subtracting

one histogram from another. This was changed to $B' = B\left(1 - \dfrac{aS_2}{2A}\right) + \dfrac{aS_1 b_t}{2}$

as given in Equation B-3. The operations include subtracting a histogram

from a constant multiplication of two histograms and adding two histograms.

5. Division of Histograms

The division of one histogram by another histogram can be performed in

a manner similar to addition and multiplication and is illustrated in the

diagram below for $z = x/y$.

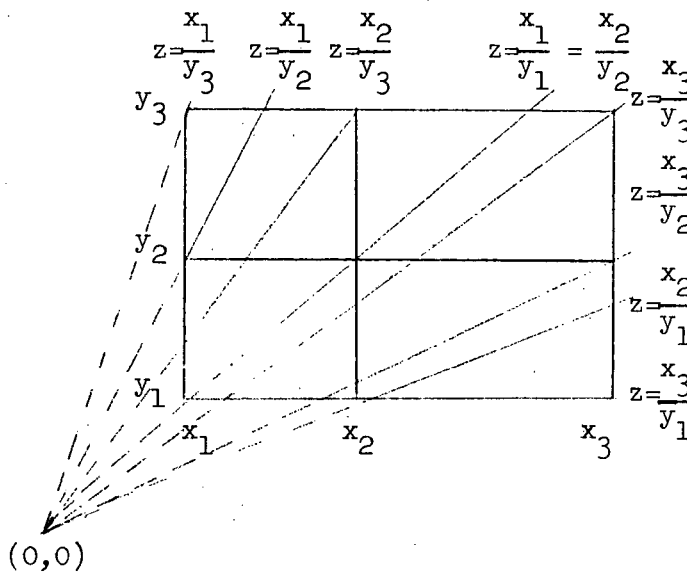Figure B-16

Division of Histograms

Division seemed to present no new problems, but when checking or adjusting

the resultant a problem arose, since the mean of the quotients is not equal

to the quotient of the means $(\bar{z} \neq \bar{x}/\bar{y})$ (Ref. 9). The choice, then, was

whether to develop a new method of acquiring a correction factor, or to

eliminate the requirement for division.

The only requirement for histogram division in the MBPM is in the exponent $-t/v$. The most logical way to make this caluclation is to take the reciprocal of v, $(1/v)$, which is simply a constant divided by a histogram, and multiply the resultant histogram by the histogram for t. The mean of $1/v$ can be determined in a straightforward manner, and the mean of the products is equal to the product of the means. This has been incorporated into the MBPM, thereby eliminating the need to divide one histogram by another histogram.

6. Conclusions on Histogram Combing Methods

The effect of the way the computer program performs histogram operations on the overall accuracy of the MBPM calculations has not been defined, but the following statements apply to individual steps of histogram combining used in the MBPM:

(1) The straight-line method of calculating probability is more accurate than the proportional method in calculating the shape and the mean of products and is more accurate in calculating the shape of sums, but is less accurate in calculating the mean of sums;

(2) The method of fixing end points by preserving the areas and moments of the end bumps tends to prevent the buildup of excessively long "tails" and gives a more realistic picture of the distribution;

(3) The method of skewing by applying a correction factor to all class limits except the end points preserves the range values better than the method of applying the factor to the entire distribution;

(4) Replacement of histogram division by multiplication with the reciprocal of the histogram improves the accuracy since there is no known way to easily correct the result of division to a known mean;

(5) Elimination of histogram subtraction improves the accuracy by removing some non-rigorous procedures from the program and by reordering the sequence of operations.

(6) When skewing will not accomplish the necessary correction, the program uses a correction factor. This can become necessary when multiplying one histogram by another histogram several orders of magnitude larger in range values.

A detailed check of histogram combining results was made for the multiplication of M identical normally distributed histograms, each with a mean of 4.0, using the straight-line method of multiplication without any other corrections or adjustments.

M	No. of Bumps	True Value of Mean	Calculated Value of Mean
2	3	16.0	17.697
2	5	16.0	16.48
2	10	16.0	16.131
5	3	1.02×10^3	3.298×10^3
5	5	1.02×10^3	1.676×10^3
5	10	1.02×10^3	1.173×10^3
10	3	1.05×10^6	8.562×10^7
10	5	1.05×10^6	1.193×10^7
10	5	1.05×10^6	2.552×10^6

Table B-1. Effect of Varying Numbers of Operations and "Bumps"

The effect of varying the number of bumps and the effect of repeated multiplications can be seen from Table B-1. The desirability of using a large number of bumps, and the necessity of correcting the mean is apparent. However, the amount of run time increases approximately as the square of the number of intervals used.

APPENDIX C

BASIS FOR CURRENT HISTOGRAMS

Appendix C.   Basis for Current Histograms

This appendix demonstrates histogram computation and contains the input histograms used in the MM '71-2 emulation. Histograms describing the background contamination (organisms/ft^2/wk) for environments are based on data obtained from fallout coupons and air samplers, and those describing the initial burden on assembly zones from swab and coupon data. The procedure used to derive histograms to represent the data is:

1. The data sample points are grouped into appropriate intervals. These intervals are chosen to increase logarithmically in length and (usually) to divide the data into ten groups.

2. The probability of occurrence of a value in each interval is calculated as the ratio of sample points in the group divided by the total number of sample points.

For example, the histogram describing the microbial burden on the octagon (assembly zone 01) due to aerobic vegetative organisms, for the Mariner '71, was derived from six groups of fallout coupon data with 144 counts of zero(considered as .1 to preserve a logarithmic abscissa) no counts of one, 18 counts between two and ten, 34 between 11 and 100, 17 between 101 and 10^3, two between $10^3 + 1$ and 10^4, and 0 between $10^4 + 1$ and 10^5. We have:

Interval	Counts
$10^{-1}(0)$ - .1	144
.1 - 1	0
2 - 10	18
11 - 100	34
101 - 10^3	17
10^3+1 - 10^4	2

Table C-1

MARINER '71 ZONAL BURDEN HISTOGRAMS

Assembly Zone	Interval (Organisms)	.01-.1	.11-1	2-10	11-100	101-10^3	10^3+1-10^4	10^4+1-10^5
	1.	.670	.000	.084	.158	.079	.009	.000
	2.	.762	.000	.054	.077	.095	.006	.006
	3.	.688	.000	.089	.080	.058	.058	.027
	4.	.397	.000	.000	.000	.165	.389	.049
	5.	.564	.000	.000	.282	.154	.000	.000
	6.	.884	.000	.070	.023	.023	.000	.000
	7.	.889	.000	.111	.000	.000	.000	.000
	8.	.865	.000	.000	.045	.090	.000	.000
	9.	.857	.000	.000	.000	.143	.000	.000
	10.	.600	.000	.000	.000	.400	.000	.000
	11.	1.000	.000	.000	.000	.000	.000	.000
	12.	1.000	.000	.000	.000	.000	.000	.000
	13.	.801	.000	.000	.138	.052	.009	.000
	14.	.424	.000	.000	.328	.157	.084	.007
	15.	.487	.000	.000	.051	.128	.308	.026
	16.	.746	.000	.135	.103	.008	.008	.000

From which follows:

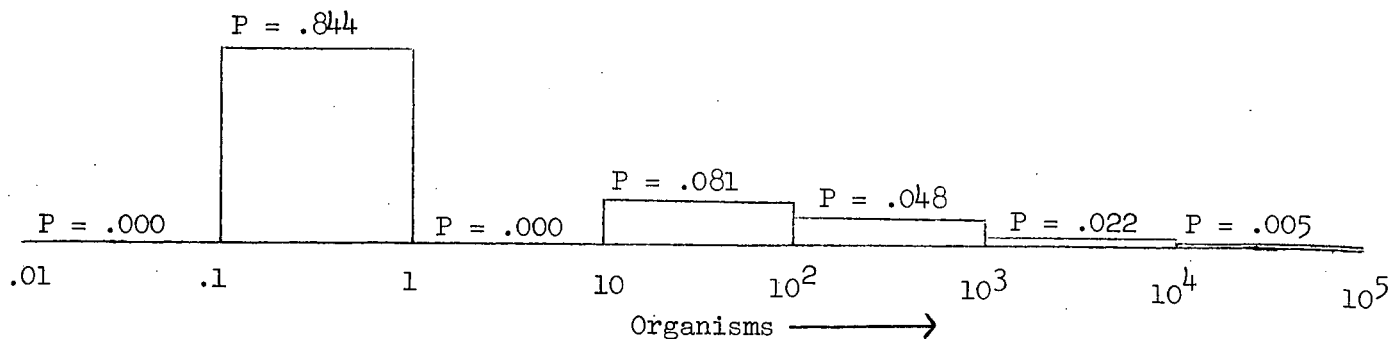| Interval	Probability
$10^{-1}(0)$ - .1	.670
.11 - 1	.000
2 - 10	.084
11 - 100	.158
10^2+1 - 10^3	.079
10^3+1 - 10^4	.009
10^4+1 - 10^5	.000

The histogram takes roughly the shape:
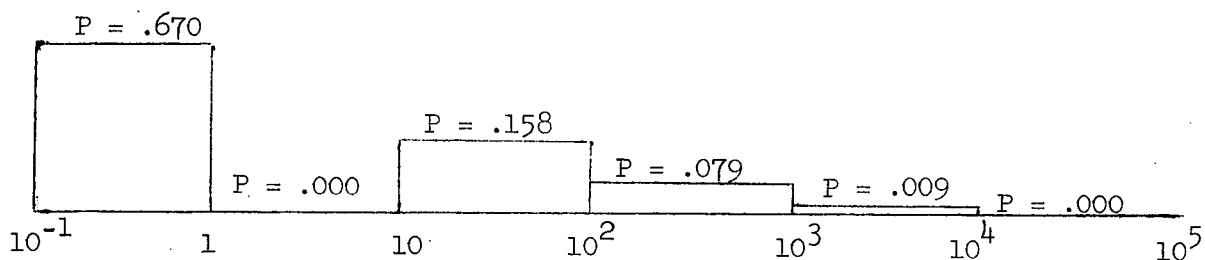
This is conveniently represented by the following array, where the entries are the probabilities of occurrence in the respective intervals:

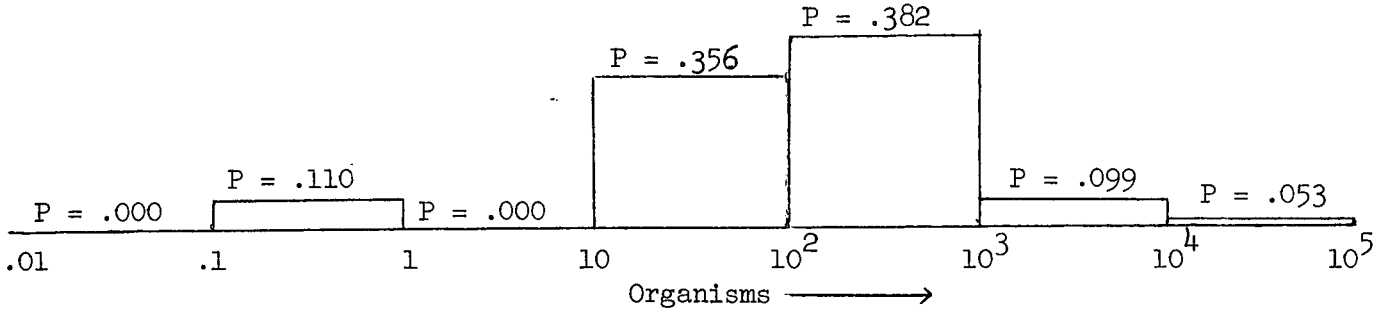| Interval	.01-.1	.11-1	2-10	11-100	$101-10^3$	10^3+1-10^4	10^4+1-10^5
Zone 01	.670	.000	.084	.158	.079	.009	.000

Histograms for all of the assembly zones are thus given in Table C-1

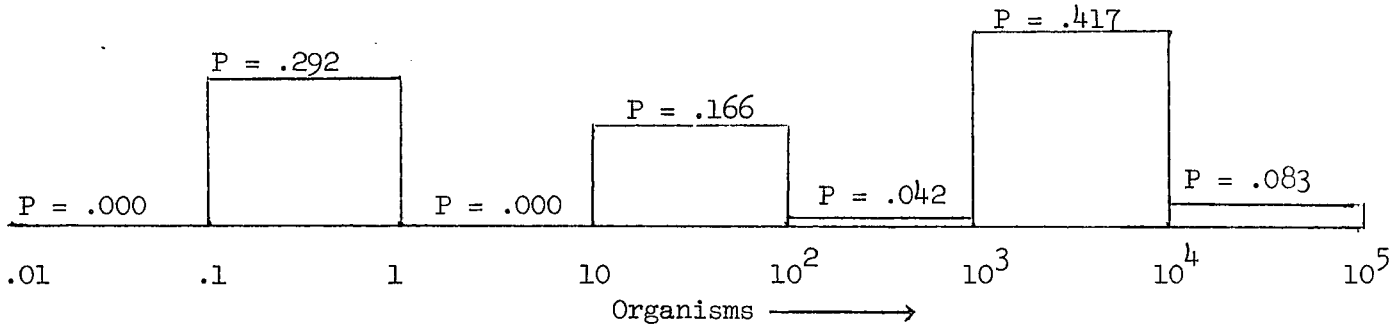The environmental histograms will be represented in rough figure form.
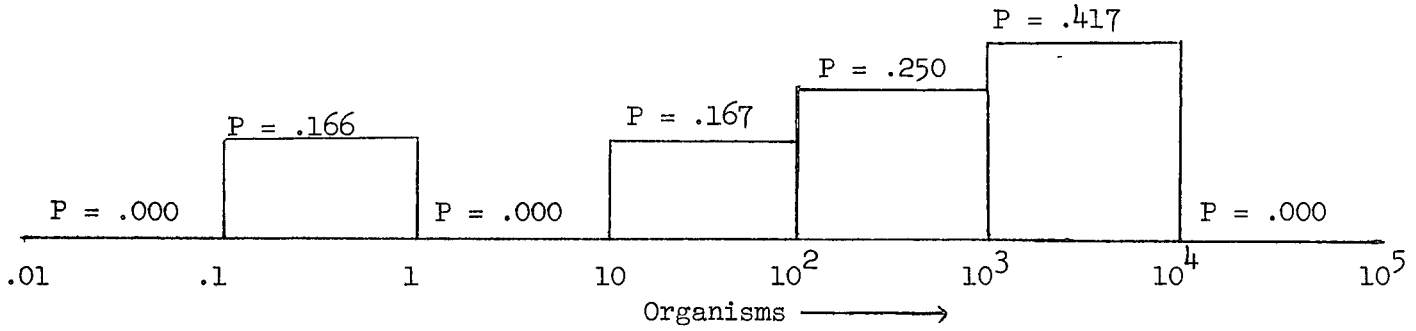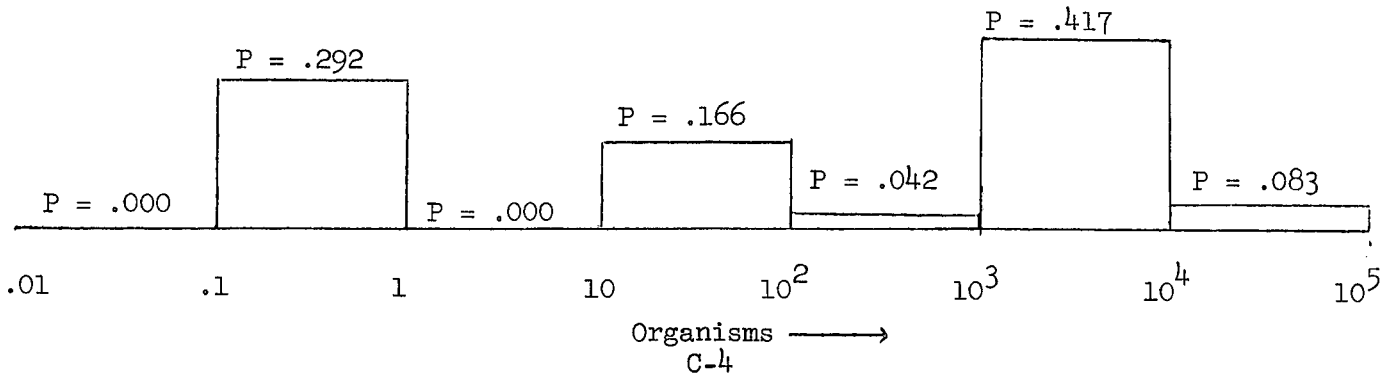
1. Tent Environment

C-3

2. High Bay Environment

P = .000   P = .110   P = .000   P = .356   P = .382   P = .099   P = .053

.01   .1   1   10 10^2 10^3 10^4 10^5

Organisms ⟶

3. Vibration Area

P = .000   P = .292   P = .000   P = .166   P = .042   P = .417   P = .083

.01   .1   1   10 10^2 10^3 10^4 10^5

Organisms ⟶

4. Space Simulator

P = .000   P = .166   P = .000   P = .167   P = .250   P = .417   P = .000

.01   .1   1   10 10^2 10^3 10^4 10^5

Organisms ⟶

5. Acoustic Lab

P = .000   P = .292   P = .000   P = .166   P = .042   P = .417   P = .083

.01   .1   1   10 10^2 10^3 10^4 10^5

Organisms ⟶

6. Hangar AO

   Same as High Bay Environment

7. Explosive Safe Facility

   Same as Tent Environment

8. Encapsulation

P = .000   P = .182   P = .000   P = .151   P = .303   P = .364   P = .000

.01   .1   1   10 10^2 10^3 10^4 10^5

Organisms ⟶
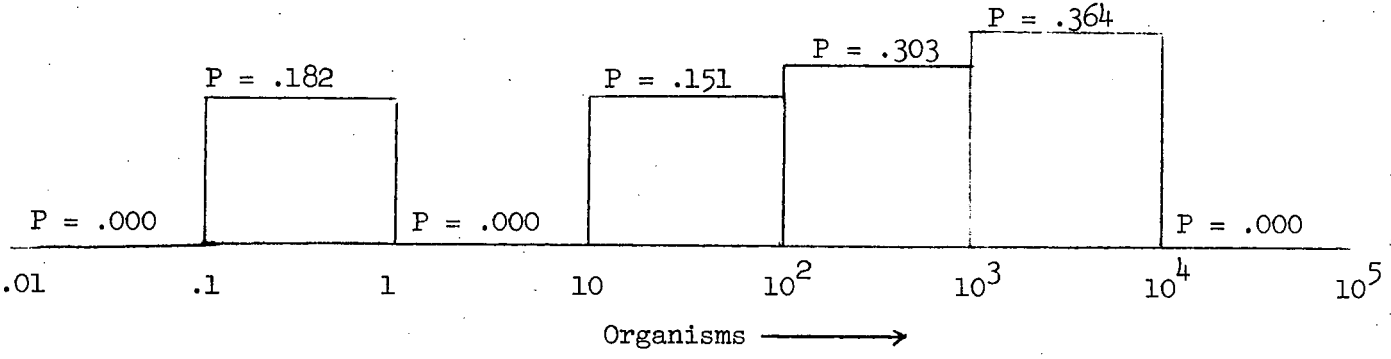
9. Nitrogen

   Same as Tent Environment.

10. Pit Area

   Same as High Bay Environment

APPENDIX D

BRIEF COST ANALYSIS

Appendix D

This appendix presents a brief cost analysis of MBPM computer runs for the Mariner 71-2 actual assembly.* The table below gives the approximate costs for running the ITP, TAS, and BPS on the Univac 1108.**

Program(s) Run	Cost ($)
ITP	90
TAS	60
BPS	60
TOTAL	210

Solar Panel Only**

ITP - TAS - BPS	80

---

* Assembly days 173 to 302 inclusive, i.e. 130 days of activity.

** Third Shift, January 1972 Computer Rates.

APPENDIX E

RESULTS OF SENSITIVITY STUDIES

Appendix E.

This appendix gives the results of sensitivity studies performed on the MM '67 and '71 emulations. Specified input parameters were increased by an order of magnitude (one log) from their values in the Base Run, or that computer run with the original parameter values. By this method, the sensitivity of the (final) predicted mean burden for all surfaces of a spacecraft at launch to certain parameters could be determined. The following table indicates the results:

Parameter Increased By One Log \ Spacecraft Emulation	M '67 [*]	M '71 [**]
Organism Mean Lifetime	.23	1.03
ETR Operational Fallout	.13	.60
Hangar AO Environment	---	.10

Table E-1. Sensitivity Study Results

[*] Entries are log increases in 95% predicted burden for all surfaces, total count.

[**] Entries are log increases in mean burden for all surfaces, spores only.

APPENDIX F

REPETITIVE OPERATIONS

FOR A SPACECRAFT EMULATION

Appendix F.   Repetitive Operations for a Spacecraft Emulation

The assembly operations used in a spacecraft buildup emulation were determined and defined as follows:

No.   Operation

1.   Move assembly manually (lift, carry, and set down)

2.   Position overhead crane

3.   Attach crane hooks

4.   Take up chain slack; hoist module with crane

5.   Move module with crane

6.   Lower module with crane; slacken the chain

7.   Detach crane hooks

8.   Inspect module/assembly and approve

9.   Lift assembly with mobile service platform fixture (MSPF)

10.   Place assembly in handling container

11.   Move in handling container

12.   Connect test cables (hoses, harnesses, cables, etc)

13.   Disconnect test cables (hoses, harnesses, cables, etc)

14.   Perform test

15.   Insert screw, bolts, etc

16.   Tighten screw, bolts, etc

17.   Loosen screw bolts, etc

18.   Remove screw, bolts, etc

19.   Decontamination (cleaning)