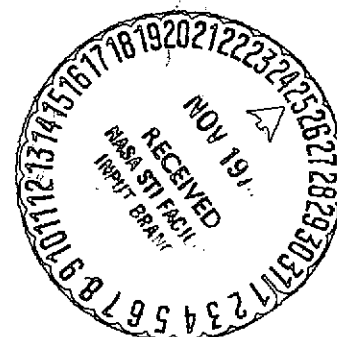# TECHNIQUES OF BIOLOGICAL

CONTAMINATION AVOIDANCE

BY ATMOSPHERIC PROBES

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TECHNIQUES OF BIOLOGICAL CONTAMINATION AVOIDANCE BY ATMOSPHERIC PROBES

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for

AMES RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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TECHNIQUES FOR AVOIDING BIOLOGICAL CONTAMINATION

OF THE OUTER PLANETS BY ATMOSPHERIC PROBES

SUMMARY AND CONCLUSIONS

Summary

The likelihood of biologically contaminating a planet by an atmospheric probe has a low probability of occurring if the probe is kept biologically clean during terrestrial operations and if the structure remains in tact until the planets life zone is completely penetrated. These appear to be reasonable conclusions even though multiple probe and flyby missions are planned to each planet during prescribed periods of biological interest, nominally twenty years after first encounter. The situation differs significantly between a flyby and an entry mission. In the former the vehicle is programmed to miss the planet's capture area from initial insertion. It is progressively controlled to assure a miss throughout the transit flight. The latter on the other hand is targeted at an aim point well within a capture radius from its first correction maneuver. Only after release of a probe is the carrier redirected to miss the planet. Even so the probability of contamination, using NASA specified growth probabilities and substantiated assumptions, is of the order of 2.11×10^{-5} for Saturn and Uranus, which is somewhat lower than the proposed NASA allocations for the two planets, 5.13×10^{-5} for an unsterilized probe.

The margin between probability and allocation is small so high standards of cleanliness, monitoring and estimating for remedial actions must be maintained in a probe program. It is not a foregone conclusion, however, that heat sterilization as practiced on prior programs (Surveyor, Ranger and Viking) needs to be employed. The use of several techniques having a good potential for lower probe costs are available and appear adequate to render a probe sterile within acceptable bounds. The techniques considered to be satisfactory for minimizing microbial load include: (1) combined heat (at 95-105°C) and gamma radiation, (2) short-term heating at 105° ± 5°C to inactivate all vegetative microbes, (3) irradiation routinely by ultraviolet (UV) light, (4) wiping by a bactericidal agent with or without a penetrant, and (5) cleanliness alone.

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Cost savings up to two-thirds can accrue and a preclusion of deliberate program stretchout are attainable if the cleanliness procedures studied are instituted. Careful surveillance of all steps, in particular, during storage and handling can inhibit growth or accumulation of spores. Remedial measures may occasionally have to be conducted but costly use of high temperature parts, testing to assure performance after repeated heat cycling, and reduced complexity of monitoring and bookkeeping can be avoided.

Conclusions

1. Targeting the spacecraft and probe to miss the planet (probe deflection procedure) yields a $P_c = 9.9 \times 10^{-5}$ probability of contamination allocation from the probe; targeting both at the planet (bus deflection procedure) lowers the allocation to 5.13×10^{-5}.

2. Contamination of a planet by exterior surfaces is precluded by cleanliness in fabrication, interplanetary exposure hazards (radiation primarily) and high entry temperatures. Contamination by internally located spores is precluded if the structure remains intact through the life zone. In prescribed life zones a 5σ structure provides this integrity.

3. Cleanliness accompanied by mild heating (90-100°C) with irradiation (γ) can keep microbial loads below 3×10^5 spores which is an objective cleanliness requirement. A mild final heat cycle or irradiation by γ-rays will inactivate vegetative bacteria thereby simplifying monitoring requirements.

4. Additive costs due to fulfilling planetary quarantine requirements can be held to twelve percent or less by use of cleanliness techniques itemized herein with no program stretchouts required.

5. Jupiter is so inhospitable to terrestrial biology that heat sterilization is unnecessary. Saturn is the most hospitable (considering current state of our knowledge of its atmosphere) so a probe to that planet should retain the highest P.Q. standards. Uranus which is least well understood is assumed to be intermediate to the other two and may be the least hospitable. Titan is not thoroughly analyzed but poses a contamination potential not found in the three outer planets examined because it will involve impact of a probe with the surface without having been subjected to high levels of trapped radiation or high ambient (auto-sterilizing) temperatures.

2

INTRODUCTION TO BIOLOGICAL CONTAMINATION

The study objective is to identify techniques needed to fulfill quarantine requirements at costs reduced from those encountered in other planetary entry or satellite lander programs. The study is restricted to contamination of the atmospheres by the entry probe even though a distinct probability exists that the spacecraft bearing the probe can contaminate the atmosphere, also. The study is also limited to the atmosphere, roughly to the cloud layers, because ambient temperatures ultimately exceed auto-sterilization levels until the probe has descended to very low levels. Thus, an entry probe is expected to be completely sterile prior to normal atmospheric breakup or surface encounter, assuming that one exists. Titan and other satellites pose special problems owing to the fact that they do have surfaces and ambient temperatures probably do not assure full sterilization prior to touchdown.

This study is essentially a continuation of a contracted effort (NASA Contract NAS 2-7328, Modification 4) which is reported in Reference 1. The effects on design, weight and cost on a previously designed Saturn/Uranus Atmospheric Entry Probe (SUAEP) were determined in that report using Viking procedures as a base and cost estimating relationships from MDAC-E efforts on Voyager Phase B and Viking preparatory studies.

This report covers a large segment of available literature and discussions held with key personnel actively engaged in planetary quarantine implementation methods. Assembly and cleanliness techniques are postulated which are believed to-be compatible with the inherently low probability of contamination of the outer planets. They are low-cost procedures which fulfill the goal of the two contract modifications.

The requirements for maintaining the outer planets in a quarantined condition insofar as terrestrial biology is concerned differ in character from those of Mars because landings on a surface are not as yet contemplated. The structures of the planets appear, at this time, to obviate penetration to a liquid or solid surface. Descent in the atmospheres is through increasingly dense gases which get hot enough eventually to destroy bacteria if structural integrity of an entry vehicle is provided in the design and aiming accuracy is

3

assured throughout interplanetary operation. This premise fulfills the agreements made in COSPAR (Committee of Space Research) negotiations; however, it does modify application of principles and design emphases in the analysis. Both can result in changes in the ultimate magnitude of costs to the outer planet programs.

The NASA established the planning philosophy and constraints for planetary quarantine in Reference 2. This document lays the groundwork for preparation of a Planetary Quarantine Plan for all unmanned planetary flight programs that have space vehicles which are intended to encounter, orbit or flyby planets of biological interest. Another NASA document (Reference 3) specifies the planetary and mission probabilities of contamination P_c and growth P_G for the planets. In general, the planets for which approved flybys and entries are in the development stages have specified contamination values in force. Relative to outer planets this is currently limited to Jupiter. However, a guideline specification sheet also exists for Saturn. In this study Saturn and Uranus probabilities of contamination and growth have been assumed to be equal.

The probability of contaminating one of the outer planets or one of its satellites by terrestrial microbiology is considered to be low if safeguards are placed on the mission from an early stage of a probe's development. To avoid biological contamination by an entry probe, safeguards such as controlling mission entry within a defined corridor, minimizing the microbial load prior to launch, and configuring the probe so that release is inhibited during high altitude (low ambient temperature) regions of the planet. Entry into an outer planet differ radically from terrestrial planets and all satellites in that surface encounter and potential break-up is not a factor in release mechanisms. The very massiveness of the planets tends to preclude contamination by two or three hazards associated with them, viz., (1) high entry velocities generate extremely high temperatures, (2) increasing density of the atmospheres and internal exothermic processes cause autosterilization temperatures to be attained eventually, and (3) trapped radiation surrounding Jupiter (and perhaps Saturn and Uranus) effectively reduce bioburdens prior to atmospheric entry.

The probability of contamination is analytically determined without a heat sterilization cycle in order to define the required number of decades of bioburden reduction to be imposed. The procedure is defined by NASA and overall allocation for each planet set by the Planetary Quarantine Officer. For a probability of contamination of 1×10^{-4} for each mission (the same value used in the Pioneer 10 and 11 missions), the allocation for Saturn or Uranus for a probe is 5.13×10^{-5}. The allocation is based on the Saturn/Uranus Atmospheric Entry Probe (SUAEP) study guideline of spacecraft targeted at the planet from the first correction maneuver. A probability of contaminating Saturn or Uranus with spores equal to 2.11×10^{-5} results in a marginal situation. Hence, a reduction of bioburden by direct action may be required to provide a margin of safety at launch.

The techniques for bioburden reduction available include dry heat sterilization of components and the assembly (see Reference 1), combined heat and gamma radiation cleanliness in fabrication combined with heat or irradiation, and cleanliness alone. Several techniques are reviewed for relative effectiveness and programmatic impact. Cleanliness combined with direct irradiation with ultraviolet is concluded to fulfill the requirements of planetary quarantine in the Jovian planet entries but not their satellites. The planets have a limited life support zone that will be encountered at high planetary atmospheric levels, whereas, the satellites possess an atmosphere too tenuous to preclude impact, probable break up, and release of buried microbial load.

The keys to avoidance of contamination in the planetary atmospheres are low initial spore levels, self sterilization in the currently defined atmospheres owing to high heat transfers to external layers of a probe, and assurance that buried or encapsulated microbes are contained until ambient temperatures attain a time-temperature condition which reduces residual bioburdens to a nonreplicating condition. The structure must be designed to withstand 5 standard deviations above defined loads to assure this. Ultimate probe failure is postulated as melting of the internal aluminum structure which is a condition that is well above life sustaining capability of any terrestrial microbes.

Schedule and cost effects indicate that a probe that is designed to with-
stand repeated heat cycles to control initial load can add up to two months to the
probe development period and up to 21% additional costs. An alternative
fabrication and control concept based on the use of a Class 100 room with either
periodic ultraviolet radiation reductions of bioload or a single heat steril-
ization cycle at 113°C can reduce the time element by one or two months and
added costs to 12%. Another alternative would employ standard spacecraft
assembly areas (Class 100,000) with biological monitoring and routine bioload
reductions by ultraviolet irradiation and/or biocidal agents coupled with
protective devices to prevent contamination. This technique ie estimated to
cost 7% more than a probe built without regard to planetary quarantine
requirements. In all cases these estimates represent a total cost to the
program of 6% or less.

This report examines the probabilities of contamination which sets the
requirements for maximum bioload that is acceptable, minimization techniques,
entry contamination by various release mechanisms, and schedule and cost impacts.
Some procedures are appended and the Jovian radiation kill capability is included
for reference. Conclusions are stated to assist in interpretation and ultimate
implementation of an outer planets quarantine plan for probes.

CONTAMINATION PROBABILITY EVALUATION

An evaluation of probe contamination probability has established the required level of initial bioburden reduction, both with and without heat sterilization. Primary emphasis was placed on the Saturn/Uranus mission and the results modified to reflect a Jupiter mission.

Saturn/Uranus

The probe contamination probability is evaluated by first establishing a maximum allowable contamination allocation. An allocation is assumed, herein, but its establishment is the prerogative of Dr. Lawrence B. Hall, the NASA Planetary Quarantine Officer. Microbe survival probabilities and initial bioburdens were then estimated and combined to yield a nominal prediction for the planetary contamination probability. A comparison of these allowable and predicted probabilities is made to identify the necessary bioload reduction and to assess the need for heat sterilization and its form.

Contamination Allocation - A maximum allowable probe contamination probability per mission was needed to provide a requirement against which the subsequent estimates of actual probe contamination probability could be compared. However, it was too early for the NASA to formally set such a requirement for outer planet probe missions. Hence, a preliminary estimate was made for purposes of this study.

The general approach to estimating a probe contamination allocation was to:
o Identify an overall contamination probability limit per mission (probe plus spacecraft) from similar mission limits given in the NASA Planetary Quarantine (P.Q.) Specification Book (Reference 3).
o Estimate the spacecraft contamination probability by modifying recent Pioneer contamination analysis to reflect the increased impact probability that results from targeting at the planet instead of targeting for a flyby throughout.
o Determine the probe allocation by taking the difference between the total mission limit and the spacecraft contamination contribution.

The basic relationship used to determine probe allocation was:

$$P_C/\text{Mission} = (P_I \times P_{C/I})_{SC} + (P_I \times P_{C/I})_{PROBE} = 1 \times 10^{-4}$$

where P_I = Impact probability

$P_{C/I}$ = Contamination probability given impact

and

$$P_C/\text{Mission} = 1 \times 10^{-4}$$

$$(P_{C/I})_{(SC)} = 1.68 \times 10^{-4}$$

$$(P_I)_{PROBE} = 1.0$$

therefore

$$(P_{C/I})_{PROBE} = [1 \times 10^{-4}] - [1.68 \times 10^{-4} \times (P_I)_{SC}]$$

The overall contamination probability limit of 1×10^{-4} is the Reference 3 value for the Pioneer 11 (Jupiter/Saturn) mission and was assumed to be valid for all probe missions to either Saturn or Uranus. The value of $P_{C/I(SC)}$ was taken directly from the (Reference 4) Pioneer analysis. The assumption of unity for the probe impact probability reflects the basic intent of the probe mission, i.e., to be captured by the planet.

Probe contamination allocation was therefore expressed in terms of spacecraft impact probability. Both a target for flyby and a target at planet condition were considered to assess the effect of targeting strategy on contamination probability. A flyby impact probability of 6.21×10^{-3} is used in the two midcourse correction trajectory analysis of Reference 4. The impact probability for targeting at the planet was estimated in the following manner.

$$P_{I(SC)} \text{ (Target at Planet)} = (P_{\bar{M}_1} \times P_{I/\bar{M}_1}) + P_{\bar{M}_2/M_1} + P_{\bar{M}_3/M_2}$$

where $P_{\bar{M}_1}$ = First maneuver failure probability = .0820

$P_{I/\bar{M}_1}$ = Impact probability given first midcourse failure = .0691

P_{M_2/M_1} = Second midcourse failure probability given first midcourse
success = .1220

P_{M_3/M_2} = Deflection maneuver failure probability given second midcourse
success = .1620

therefore

$P_{I(SC)}$ = .00566 + .1220 + .1620 = 2.897 x 10^{-1}

It was assumed that the first midcourse maneuver would initiate targeting at the planet. Hence, failure to accomplish the first midcourse would result in a low impact probability. Failure of subsequent maneuvers, however, would result in the continuation of a trajectory with a high probability of planetary capture. An impact probability of unity was therefore assumed for these subsequent maneuvers. Midcourse failure probabilities and first midcourse impact probability were taken from Reference 4. Deflection failure probability was estimated by linear extrapolation with number of manuevers. Note that the $P_{I(SC)}$ was substantially greater than that for flyby targeting and approximately equal to the sum of the failure probabilities of the maneuvers following the first midcourse.

Incorporation of these spacecraft impact probabilities yielded the following probe contamination allocations.

$P_{C(PROBE)}$ (TARGET FOR FLYBY) = 1.0 x 10^{-4} - 1.04 x 10^{-6} = 9.9 x 10^{-5}

$P_{C(PROBE)}$ (TARGET AT PLANET) = 1.0 x 10^{-4} - 4.87 x 10^{-5} = 5.13 x 10^{-5}

As shown, the target at planet strategy does reduce the allowable probe allocation but not by a substantial amount. In the flyby case, almost all of the mission P_C can be allocated to the probe whereas targeting at the planet results in a near equal apportionment of P_C between spacecraft and probe.

Survival Probability - The evaluation of probe microbe survivability followed the analytical approach of Reference 4 with two key expansions. First, the probe was considered as three parts; the multilayer insulation

(MLI) blanket, the ablative heat shield and the remainder or interior of the probe. This subdivision, shown in Figure 1, allowed the potential variations in microbe survivability at different probe locations to be considered. The second expansion was to take into account the unique location of the outer planet life zone compared to Earth and Mars. As shown in Figure 2, this zone does not extend down to the surface (like Mars) but is suspended in the atmosphere. These definitions are based on the work of Taylor, et. al, at the Jet Propulsion Laboratory and appear in Reference 5. As a result, the probe will pass through, but not take up, permanent residence in the life zone. A somewhat modified approach to the assignment of microbe release probability was therefore taken to reflect the beneficial impact of a transitory rather than permanent penetration of the life zone.

PROBE MICROBE LOCATIONS
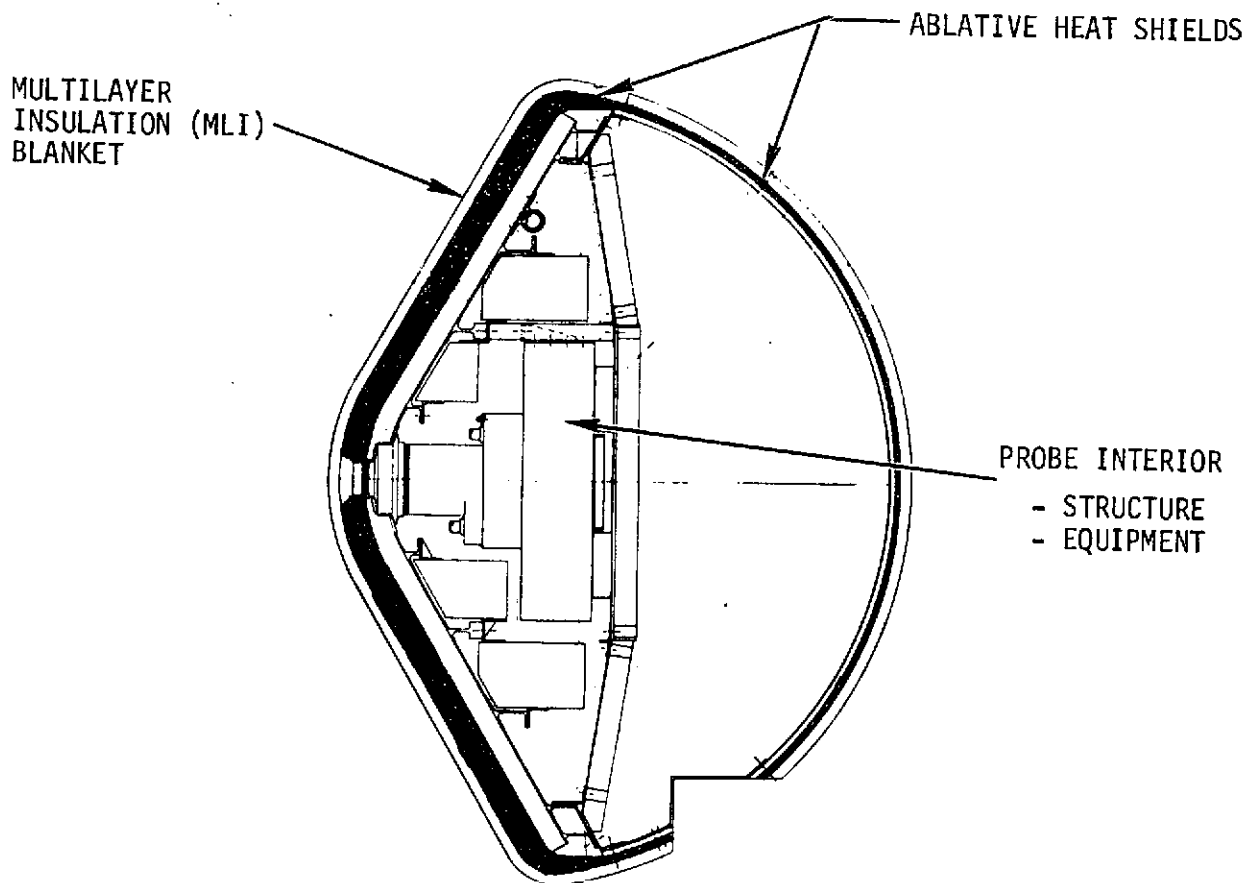
Figure 1

PLANETARY LIFE ZONE DEFINITIONS

INCLUDING LIFE ZONE DEFINITIONS

JUPITER (NASA SP-8069)

COOL   WARM

NOMINAL

PIONEER 10 - KLIORE ATM

LIFE ZONE

PRESSURE, P (ATM)

T (100's K)

SATURN (NASA SP-8091)

COOL

NOMINAL

WARM

LIFE ZONE
(263-383°K)

TEMPERATURE, T (100's K)

URANUS (MDC S/UEP-SI-24)

NOMINAL

COOL

WARM

LIFE ZONE

PRESSURE, P (N/m²)

T (100's K)
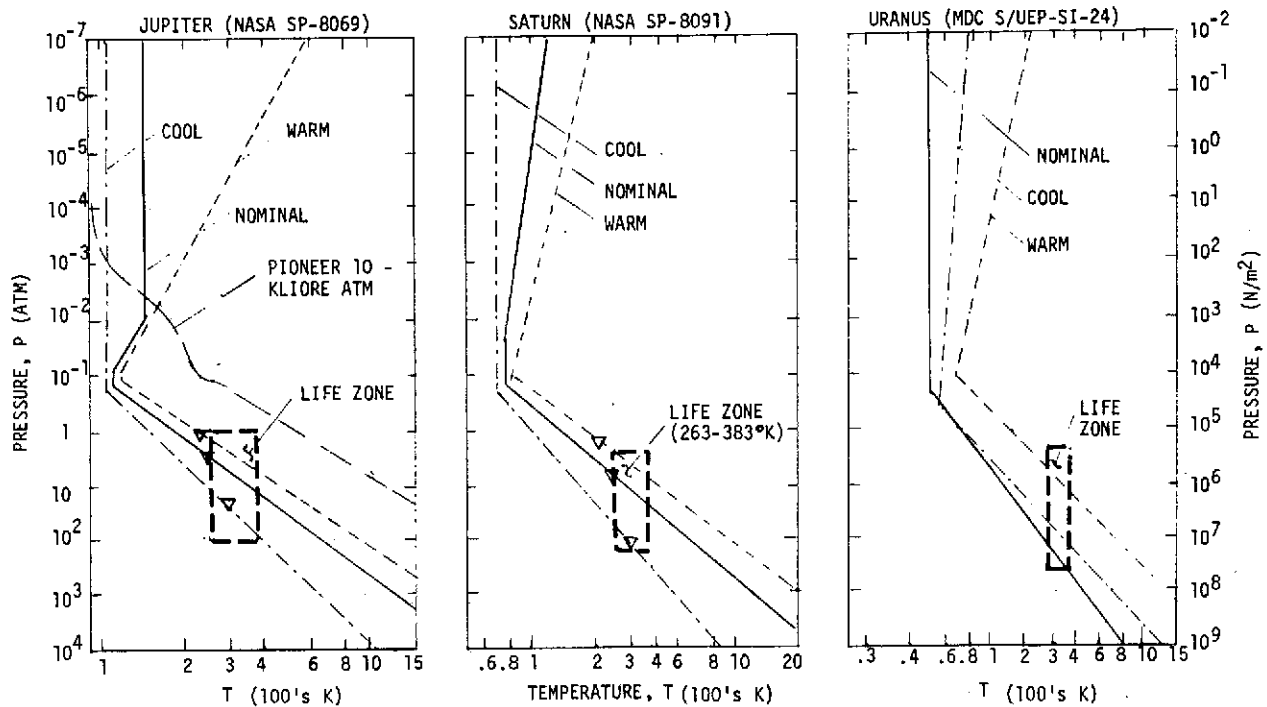
Figure 2

Results of the survivability analysis are summarized in Figure 3. As indicated the space environment encountered during transit was estimated to have little effect on microbe population. Similarly, entry radiation was considered to have a negligible effect because there still is no firm evidence of a significant trapped radiation belt around either Saturn or Uranus. Entry temperature, however, is expected to noticeably affect bioload survivability. The MLI value of 10^{-3} represents a nominal estimate and equal to the overall microbial survivability on the Pioneer spacecraft (Reference 4). However, values ranging from near unity to 1×10^{-6} may be possible depending on the manner in which the MLI is removed from the probe and the ballistic coefficient of the resulting fragments. Although a detailed analysis of this phenomenon was beyond the study scope, a sensitivity assessment was conducted and is discussed in later paragraphs. The survival probability of 1×10^{-4} microbes in the ablative material was used as a conservative estimate. A discussion of the processes appears in the section

MICROBE SURVIVAL/GROWTH PROBABILITY SATURN/URANUS PROBE

FACTOR	PROBE LOCATION		
	MULTILAYER INSULATION	ABLATIVE	INTERIOR
SPACE ENVIRONMENT			
RTG RADIATION (S/C)	9×10^{-1}	1.0	1.0
UV RADIATION (NATURAL)	1.0	1.0	1.0
VACUUM-TEMPERATURE	1.0	1.0	1.0
SPACE TRANSIT (METEORS, ETC.)	1.0	1.0	1.0
FLYBY PLANET RADIATION	1.0	1.0	1.0
ENTRY ENVIRONMENT			
RADIATION	1.0	1.0	1.0
TEMPERATURE	1×10^{-3}	1×10^{-4}	1.0
PLANETARY ENVIRONMENT			
REMOVAL FROM PROBE	1.0	1×10^{-1}	1×10^{-5}*
SURVIVAL TO LIFE ZONE	1.0	1.0	1.0
DEPOSIT IN LIFE ZONE	1×10^{-1}	1×10^{-1}	1×10^{-1}
GROWTH & REPLICATION	1×10^{-6}	1×10^{-6}	1×10^{-6}
	9×10^{-11}	1×10^{-12}	1×10^{-12}

*ESTIMATED PROBABILITY OF CATASTROPHIC STRUCTURAL BREAKUP OF PROBE ABOVE OR WITHIN LIFE ZONE

Figure 3

on Minimization of Microbial Load. If bondline temperatures at entry approach design values, the ablative would be completely sterilized.

The most significant survivability considerations are those associated with the post entry or planetary environment. The factor, normally expressed as a single release probability, is treated in three parts: the removal of material containing microbes from the probe, their subsequent survival to the

life zone, and the transfer or deposit of these microbes from the probe material into the life zone. The probe removal probability for the non-structural MLI is assumed to be unity while the value of 10^{-1} for ablative material conservatively reflects the possibility that uncharred material might be torn or broken off. The key factor, however, is the recognition that microbes in the probe interior cannot be released unless a catastrophic structural breakup occurs before the probe descends below the life zone in a normal entry. The 10^{-5} removal probability for internal microbes is estimated using current structural design safety margins and reflects a vented probe design that minimizes differential pressure even at very high local ambient pressures. A major uncertainty remains in the loads resulting from an off-nominal entry trajectory. Hence, the sensitivity of the contamination probability to probe structural integrity is assessed in later paragraphs.

The probability of survival to the life zone is taken as unity. This appears to be conservative for fragments removed from the probe before most of the kinetic energy has been dissipated. However, there is not enough test data (or analysis time) to justify a lower probability.

The consideration of depositing in the life zone essentially refers to the number of microbes that may be removed from probe fragments as they pass through the life zone and that can take up permanent residence there. While some surface microbes might be removed by a scouring action of the atmosphere, it is difficult to postulate a mechanism that transfers organisms that are buried, either from inside equipment or between layers of MLI. Further, natural convection currents in the atmosphere may cause recirculating of deposited microbes to lower altitude, high temperature regions which inherently create a natural sterilization process. Therefore, the 1×10^{-1} deposit probability seems excessively conservative; further study by exobiologists and atmospheric physicists is recommended.

The 1×10^{-6} probability of growth and replication was taken from the preliminary P.Q. specification for Saturn and assumed applicable to Uranus. This appears to be appropriate even though the P_G for the more hospitable environment of Mars is also 1×10^{-6}. Discussions with the Planetary Quarantine Officer confirmed that this is appropos at this design stage; a one decade

reduction on outer planet P_G is a future possibility. However, for purposes of this study the conservatism associated with a 1×10^{-6} value was retained.

Initial Bioburden - The initial bioburden is estimated by determining surface areas and nonmetallic volumes of each probe element (MLI, ablative, interior) and applying a microbial density factor to each location. Both the number of spores and of total microbes (spores plus vegetative organisms) are estimated to allow eventual comparison of contamination probability with and without heat sterilization. The data and results of this evaluation are summarized in Figure 4.

INITIAL PROBE BIOBURDEN ESTIMATES

PROBE ELEMENT	TYPE	SIZE	SPORE DENSITY	BIOBURDEN (1×10^5 MICROBES) SPORES*	TOTAL**
MULTILAYER INSULATION (MLI)	SURFACE AREA	$2,107,000 \text{ cm}^2$	$.1/\text{cm}^2$	2.11	21.1
ABLATIVE HEAT SHIELDS	SURFACE AREA NONMETALLIC VOLUME	$18,900 \text{ cm}^2$ $26,700 \text{ cm}^3$	$.1/\text{cm}^2$ $15/\text{cm}^3$	.02 4.00 (4.02)	.2 40.0 (40.2)
INTERIOR	SURFACE AREA NONMETALLIC VOLUME ELECTRONICS VOLUME	$261,000 \text{ cm}^2$ $81,000 \text{ cm}^3$ $7,000 \text{ cm}^3$	$.1/\text{cm}^2$ $15/\text{cm}^3$ $120/\text{cm}^3$	.26 12.15 8.40 (20.81)	2.6 121.5 84. (208.1)
			AREA SUBTOTAL	2.39	23.9
			VOLUME SUBTOTAL	24.55	245.55
			GRAND TOTAL	26.94	269.4

* ASSUME SUBSEQUENT HEAT STERILIZATION CYCLE
** SPORES PLUS VEGETATIVE ORGANISMS; HEAT STERILIZATION NOT MANDATORY

Figure 4

The very large MLI area shown represents the total surface area of 32 layers of mylar plus 31 layers of nylon net separators. The size of the ablative microbe locations includes both the forward and aft heat shields. Probe interior areas are calculated from current probe drawings and include mated, exposed and equipment internal surfaces. Equipment package internal surface areas were estimated to be twice the external surface area of the package. Interior nonmetallic volumes are also determined from probe layouts and include the actual volume of insulation and fiberglass honeycomb structure.

The volume of electronic piece parts inside science and subsystem equipment is estimated from total package weights.

A nominal microbial density for surface areas of 0.1 spores/cm^2 is used at the recommendation of the Exotech Systems Inc. The nominal density for nonmetallic volumes of 15 spores/cm^3 was established by assuming the midpoint of the microbial density range given in P.Q. Specification Sheet Number IV-2. (See Reference 3). The 120 spores/cm^3 nominal density that is applied to the electronics volume represents 80% of the maximum value shown on Reference 3, Sheet IV-2. A greater than midpoint density was selected to compensate for a still indeterminate volume estimation. Total bioburdens (spores plus vegetatives) were estimated by assuming that spores comprise 10% of the total bioload. A total bioburden estimate was included so that elimination of protracted heat sterilization could be considered. Limiting the bioburden to spores alone essentially assumes a subsequent heat sterilization cycle to inactivate the large number of more heat sensitive, vegetative organisms (Reference 3, Section V).

A comparison of estimated probe bioburden with the measured bioloads of actual spacecraft is presented in Figure 5. As indicated, the bioload of the probe interior alone is greater than for either Pioneer or Mariner. Considering the relatively small size of the probe, this indicates an inherent conservatism in the probe estimating procedures. Further analysis is included in Appendix A.

Contamination Probability - The probability of contamination of the probe was calculated and compared with the contamination allocation to identify the degree of bioload reduction required and to assess the need for heat sterilization. A summary of the basic probability data used is shown in Figure 6 for both a heat sterilization (spore bioburden) and a nonheat sterilization (total bioburden) case. The basic relationship used to calculate contamination probability was

$$P_C = 1 - (1-P_{SG})^n$$

where P_C = contamination probability

P_{SG} = microbe survival/growth probability

n = initial number of microbes

INITIAL BIOBURDEN COMPARISON

o   NO HEAT STERILIZATION

o   TOTAL BIOLOAD (SPORES AND VEGETATIVES)

APPLICATION	BIOBURDEN
PROBE - MLI	2.11×10^6
ABLATIVE	4.02×10^6
INTERIOR - VOLUME	2.08×10^7
- AREA	$\dfrac{2.6 \times 10^5}{(2.71 \times 10^7)}$
MARINER 8 (H)*	1.2×10^4
MARINER 9 (MM'71)*	3.1×10^4
PIONEER 10 (F)	1.4×10^4
PIONEER 11 (G)	2.5×10^5

*REFERENCE 6

Figure 5

Derivation of the values for P_{SG}, n, and the P_C allocation were discussed in previous paragraphs. As indicated in Figure 6, the anticipated value of P_C is below the contamination allocation if only spores are considered but exceeds this allocation if a total microbe bioburden is used. Further, the MLI contamination contribution is a dominant factor; the P_C of the ablative and interior elements are below the allocation even in the total bioload case. This indicates that MLI bioload reduction procedures are needed to deactivate the vegetative organisms. A one decade reduction of MLI spores might also be desirable to achieve a more comfortable margin. Similarly, some reduction in probe interior vegetative organisms would provide a larger margin between a current specification-based prediction and an allowable contamination probability. However, this probe interior reduction may be possible without resorting to long, high temperature sterilization procedures that adversely affect equipment design. This is discussed in the section on microbial load minimization.

PROBE CONTAMINATION PROBABILITY ESTIMATES

(SATURN/URANUS P_C ALLOCATION = 5.13×10^{-5})

PROBE ELEMENT	P_{SG}	SPORE BIOBURDEN*		TOTAL BIOBURDEN**	
		n	P_C	n	P_C
MULTILAYER INSULATION (MLI)	9×10^{-11}	2.11×10^5	1.90×10^{-5}	2.11×10^6	1.86×10^{-4}
ABLATIVE HEAT SHIELDS	1×10^{-12}	4.02×10^5	4.02×10^{-7}	4.02×10^6	4.02×10^{-6}
INTERIOR	1×10^{-12}	2.08×10^6	$\underline{2.08 \times 10^{-6}}$	2.0×10^7	$\underline{2.08 \times 10^{-5}}$
TOTAL PROBE CONTAMINATION PROBABILITY:			2.11×10^{-5}		2.11×10^{-4}

* SUBSEQUENT HEAT STERILIZATION REQUIRED

** HEAT STERILIZATION NOT MANDATORY

Figure 6

The sensitivity of this nominal P_C estimate to the key P_{SG} factors of MLI entry survivability and probe structural integrity was also assessed. The results are presented in Figures 7 and 8, respectively. The MLI data shows that (A) if a worst case assumption of near unity entry P_{SG} is made, an additional spore bio-load reduction of 3 decades would be needed. However, (B) a slightly greater than two decade reduction in the entry P_{SG} would essentially eliminate the need for any special sterilization procedures. The structural integrity assessment indicates that if a more conservative, 5σ structural relative to catastrophic breakup were assumed, about a factor of 33 reduction in interior spore bioload would be realized. This is still a much less severe requirement than the 8 to 12 decade reduction that is understood to be the Viking goal. However, a one decade lower probability of structural breakup would provide sufficient contamination margin to remove any consideration of reducing the number of

CONTAMINATION SENSITIVITY TO MLI ENTRY SURVIVAL PROBABILITY
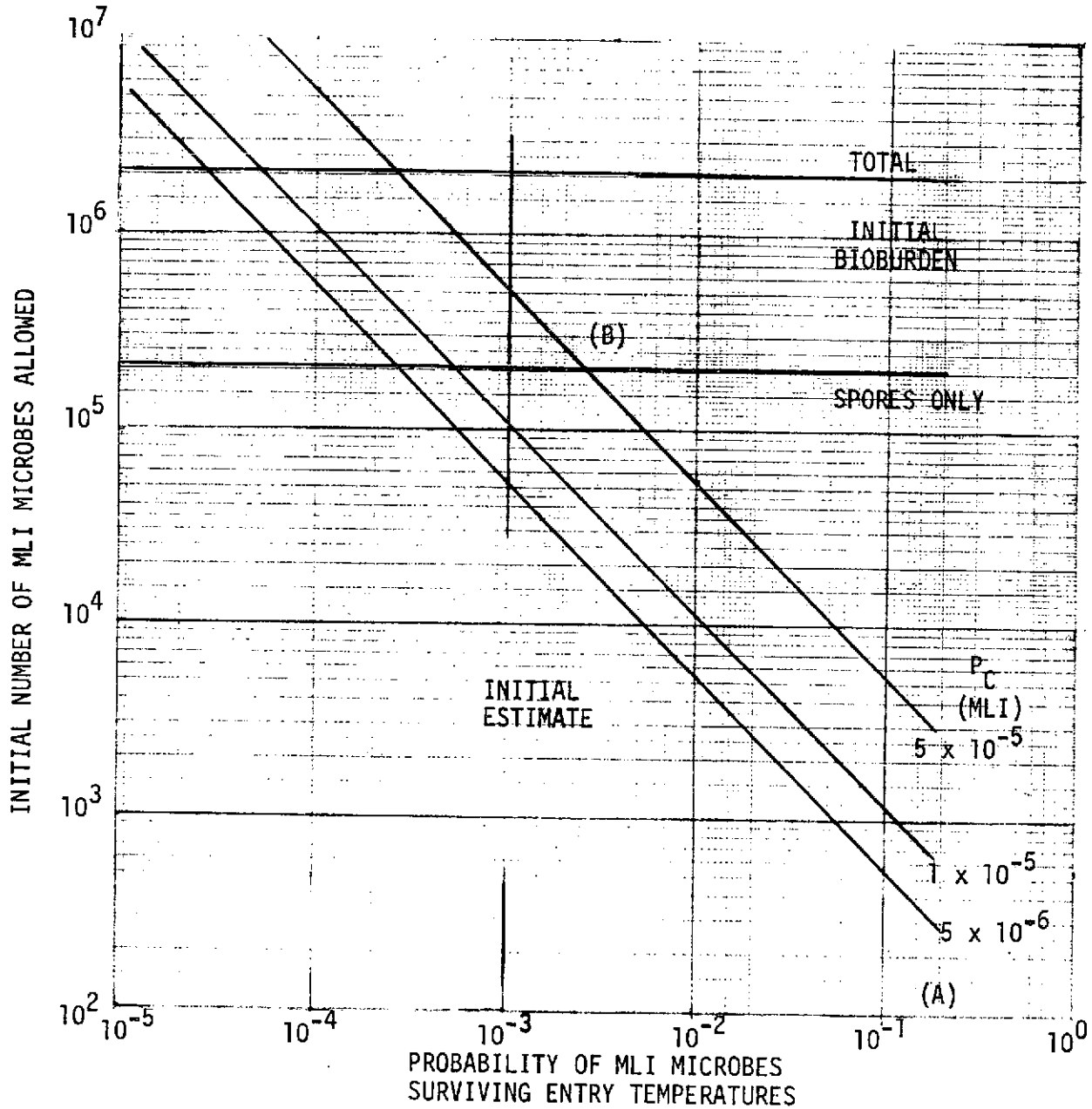
Figure 7

vegetative organisms in the probe interior. Hence, it appears that the results of a more detailed analysis would range from a mild application of heat sterilization to complete elimination of heat sterilization.

CONTAMINATION SENSITIVITY TO PROBE STRUCTURAL INTEGRITY
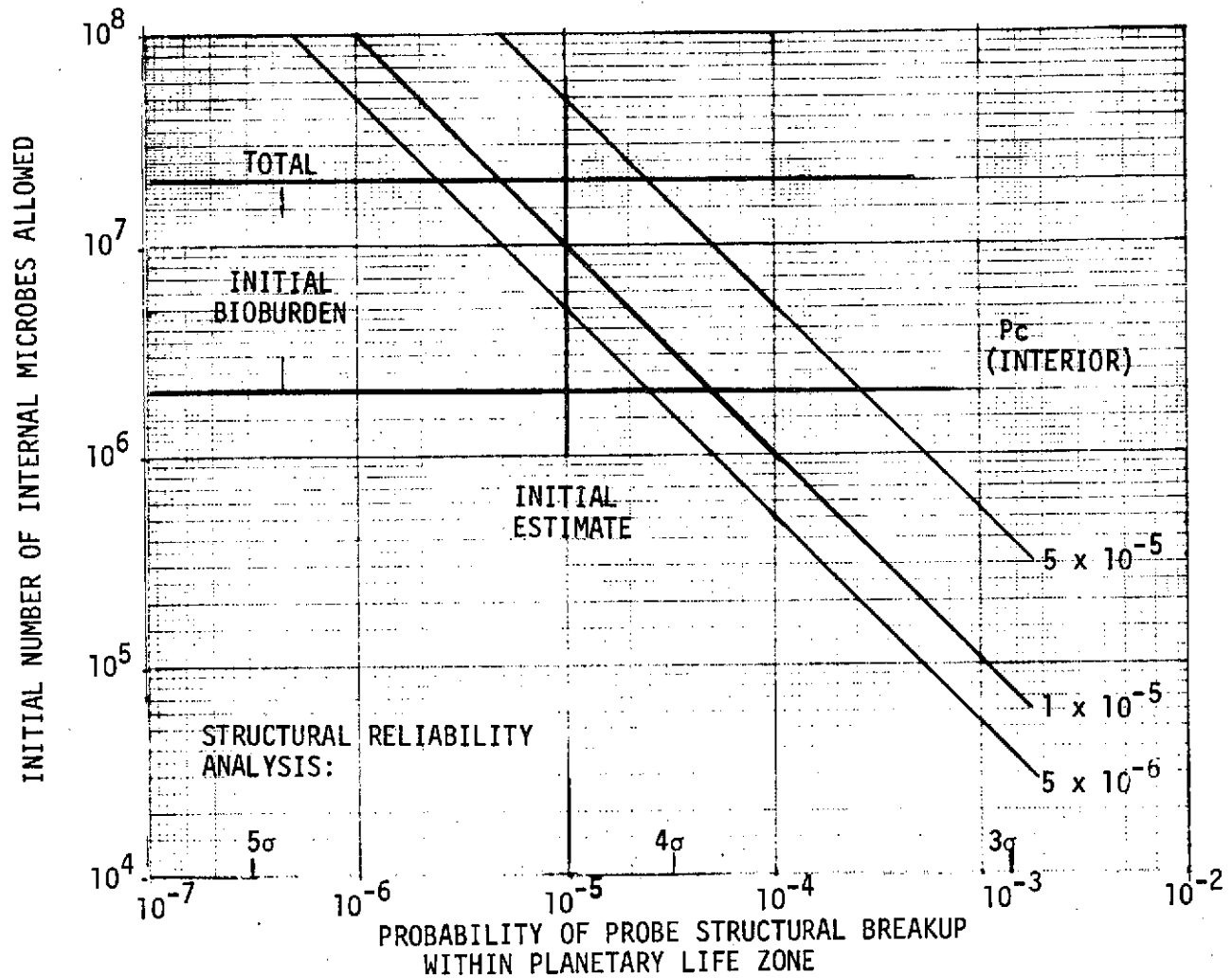
Figure 8

Jupiter

The evaluation of a Jupiter probe contamination probability was made in the same manner as that previously discussed for Saturn/Uranus. The results, summarized in Figure 9, reflect changes in contamination allocation and survival probabilities that were unique to a Jupiter mission. The slightly higher probe contamination allocation is the total mission allocation for the Pioneer/Jupiter mission (Reference 3, Sheet VI-2). Spacecraft contribution to contamination was negligible because of its low, 2.7×10^{-7} value of $P_{C/I}$

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PROBE CONTAMINATION PROBABILITY EVALUATION
(JUPITER)

o ALLOWABLE PROBE PC/MISSION = $6.4 \times 10^{-5} = 1 - (1 - P_{SG})^n$

SURVIVAL PROBABILITY (P_{SG})	MLI	ABLATIVE	INTERIOR
SPACE - RTG RADIATION	9×10^{-1}	1.0	1.0
ENTRY - RADIATION	1×10^{-5}	1.0	1.0
- TEMPERATURE	1×10^{-3}	1×10^{-4}	1.0
PLANET - REMOVAL FROM PROBE	1.0	1×10^{-1}	1×10^{-5}
- DEPOSIT IN LIFE ZONE	1×10^{-1}	1×10^{-1}	1×10^{-1}
- GROWTH AND REPLICATION	1×10^{-6}	1×10^{-6}	1×10^{-6}
TOTAL	9×10^{-16}	1×10^{-12}	1×10^{-12}

INITIAL BIOBURDEN n ∿ (10^5 MICROBES)

	MLI	ABLATIVE	INTERIOR
SPORES	2.11	4.02	20.81
TOTAL	21.1	40.2	208.1

CONTAMINATION PROBABILITY (P_C)

	MLI	ABLATIVE	INTERIOR
SPORES BIOBURDEN	1.90×10^{-10}	4.02×10^{-7}	2.08×10^{-6}
TOTAL BIOBURDEN	1.90×10^{-9}	4.02×10^{-6}	2.08×10^{-5}

Figure 9

(Reference 7). The MLI survival probability was reduced by a factor of 10^{-5} because of the biocidal effect of the Jovian trapped radiation belt. The resulting probe contamination probability is within the allocation for both spore and total bioburdens and is significantly less than the Saturn/Uranus estimates. Hence, no special, bioload reduction provisions, such as heat sterilization, appear necessary for a Jupiter probe.

MINIMIZATION OF MICROBIAL LOAD

Current planetary quarantine standards require microbiological control in the construction of outer planetary probes. These efforts can be time consuming and can breed costly paperwork in tracking parts to completion. It is pated that some relaxation in these standards may be forthcoming, or that alternate procedures may be adopted to satisfy the standards without the required overkill currently in effect.

For example, the major contribution of microbial contaminants from the current probe design to outer planets will arise from flaking or chipping of the multilayer insulation (MLI) during entry. This particular component can be heat sterilized to assure that contamination due to organisms on an inner layer of the MLI does not occur. It is also possible to reduce its load by irradiation.

Regardless of whether the final probe assembly will be required to undergo heat sterilization or some form of heat-irradiation sterilization, a knowledge of the microbial burden on the probe is required. If no final treatment is required, the microbial load must be known to be less than a predetermined maximum load. If a final bioload reduction is required, by either heat or heat-irradiation, the microbial load must be known to dictate the amount of treatment required to obtain the desired degree of microbial load reduction. This microbial burden can be determined only by monitoring of the probe components during assembly and by enumeration of the surface load of the finally assembled probe.

Minimization Methods

Minimization of the total microbial load during fabrication is needed to make estimation practical. If no final heat or heat-irradiation treatment is required, minimum numbers must be attained at final assembly in order to assure planetary quarantine by design practices only. For example, the maximum allowable bioload (spores) which would not contaminate the target planet is estimated to be 3×10^5 to prevent contamination for an unsterilized probe. Monitoring in this instance would include the determination of total microbial flora. That is, both vegetative cells and spores would have to be counted. If a final heat treatment is specified, the microbial load must be known

in order to use the shortest possible terminal sterilization cycle in order to minimize heat and/or radiation damage to components and to minimize the elapsed time required for the treatment. In addition, only total spore counts would be required during assembly and of the finally assembled probe. This results from the fact that vegetative cells are more readily killed by the final treatment than are the bacterial spores. By the time the spores are killed all vegetative cells would have been killed anyway, regardless of their numbers. This characteristic can be employed to eliminate all vegetatives by a short duration, low temperature heat cycle whose sole purpose is reduction of assay time. Figure 10 itemizes the currently applied elements in a sterilization program and an alternate (I) that cleanses a probe with only one cycle used as a vegetative removal procedure.

MINIMIZATION OF BIOLOAD DURING MANUFACTURE

PRESENT	◄─── STANDARDS ───►	ALTERNATE
DRY HEAT: REPEATED REDUCTIONS (~4)	STERILIZATION	DECONTAMINATION PLUS 1 HEAT CYCLE OR HEAT-RADIATION
BAGGED WITH REMOVAL IN (UN)CONTROLLED ENVIRONMENT	HANDLING	BAGGED:--REMOVAL ALWAYS IN CONTROLLED ENVIRONMENT: LAMINAR FLOW BENCH; UV IRRADIATION
MIXTURE OF NORMAL AND CLASS 100,000 ROOM	ASSEMBLY AREA	ALL ASSEMBLY WORK IN LAMINAR FLOW BENCH
DEFINED FOR CLEAN ROOM ONLY	WORK ATTIRE	CAP, SUIT AND GLOVES WHILE ASSEMBLING
COMPONENTS, SPECIFIED SURFACES AND COUPONS	MONITORING & ASSAYING	COMPONENTS, SPECIFIED SURFACES AND COUPONS; ROOM CHECK FREQUENCY: TWICE WEEKLY
UNKNOWN PROCEDURE	DECONTAMINATION	USUALLY HIGH LEVELS WIPED WITH 90% ISOPROPYL ALCOHOL OR ETHYLENE OXIDE IN DIMETHYL SULFOXIDE PENETRANT
SWABBED, CULTURED AND ENUMERATED BIOLOAD	FINAL SAMPLING	SWABBED CULTURED AND ENUMERATED BIOLOAD
ASSEMBLY, BIOSHIELDING AT PLANT WITH RTG INSTALLATION AND RECYCLING TSC AT KSC	OPERATIONS	ASSEMBLY, BIOSHIELDING AT PLANT WITH ALL REPAIR AND RECYCLING AT PLANT

Figure 10

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Probe Assembly Minimization Procedures - In order to minimize but properly monitor the microbial burden during probe assembly the following procedures are recommended. They are not costly and are believed to be the necessary minimum to maintain cleanliness required (minimize microbial burdens) and to lessen the work load of the microbiologist in monitoring. The monitoring requirements throughout serve two purposes: The first is to determine the final load on the probe; the second, and equally important, to insure that microbial burdens do not increase at unexpected rates during assembly due to laxity in cleanliness procedures or in acceptance of unusually contaminated components. If components are determined to be excessively contaminated, last minute changes in the final sterilization cycle or the establishment of other emergency remedial measures would be instituted. The following concept (Alternative II) is recommended:

- o All assembly work is to be contained in an environment that meets class 100,000 room specifications, i.e., having no more than 100,000 particles per ft^3 greater in size than 5 microns.

- o Unwrapping of components for assembly and all assembly of components to the probe are to be conducted in a microbiological, laminar-flow bench which provides sufficient personnel working space yet does not allow the probe itself to be in contact with ambient air.

- o Cap, suit, and gloves are to be worn by persons working in the laminar-flow probe assembly area.

- o During nonworking hours high intensity ultraviolet lighting is to be used to flood the entire assembly room. This will daily reduce the load of microorganisms which build up on exposed surfaces during working hours.

- o On receipt of a component in the assembly room, it is thoroughly swabbed for its surface microbial load as described in the procedure presented as Appendix B. After swabbing, the component will be placed in sterile wrapping material described in procedure given in Appendix C and stored until its assembly time. Components having excessively high levels of contamination could be wiped down with 90% isopropyl alcohol to reduce their microbial burden, or with a mixture of ethylene oxide and dimethyl sulfoxide to render them sterile. (Dimethyl sulfoxide is a very effective penetrant.)

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o Just prior to assembly each component is treated with high intensity
  ultraviolet irradiation within the laminar flow hood. For most compo-
  nents a turn-table or rotisserie is to be provided. At mating, both
  mated surfaces are swabbed to determine their microbial burden and, if
  the load is excessively high, the unit will be cleaned by one of the
  above-mentioned methods and rechecked.

o Twice weekly swab samples are to be obtained in the assembly room and
  under the assembly hood to ascertain that cleanliness procedures are
  being maintained in the general work area.

o The finally assembled probe is to be thoroughly sampled prior to instal-
  lation of a bioshield or ground handling cover to determine its final
  launch load or to specify the degree of final heat or heat-irradiation
  treatment.

A final sterilization cycle consists of either dry heat alone at 113°C or dry
heat (at 105°C) combined with high energy gamma irradiation. Sandia Labora-
tories has shown a savings of both time of exposure and temperature level is
obtained using this simultaneous exposure technique. This latter possibility
can be implemented at a nominal cost to the probe development and fabrication
program. The relatively small size of the probe makes a gamma radiation
installation manageable (see also Synergistic Effects of Thermoradiation).

If indeed a final heat or heat-irradiation treatment is conducted, the
degree of microbiological monitoring could be reduced by about 30% since only
total spore counts, and not total bacterial counts, need be conducted.

Ultraviolet Radiation Sterilization - Manufacturing of the probe can take advan-
tage of the bactericidal application of ultraviolet radiation to reduce the
probe bioburden daily. A commercial mercury vapor lamp located above the work
area can be operated during off-hours of the probe assembly period to keep bac-
teria growth in check and, thereby, keep bioburden below the limits to be
specified for surface and mated surfaces.

Ultraviolet radiation between 180 and 300 nanometers destroys bacteria,
mold yeast, and virus. Because of the absorption in the ozone layer of Earth's
upper atmosphere, virtually none of this short-wave length solar radiation
reaches the surface. Radiation at 2650 Å (265 nm) produces the optimal bacter-

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icidal rates according to the Illuminating Engineering Society (Reference 8).
Most commercial ultraviolet bactericidal lamps operate with a peak output at
2537 Å, a wavelength that is only 85% as effective as 2650 Å. Lamps of this
type with or without quartz glass are usable.

The bactericidal effectiveness of ultraviolet radiation results from the
absorption of radiant energy by nuclear protein, the vital part of the bacteria,
after transmission through air, water and the ordinary protein of the bacteria.
In contrast, theoretically more lethal energy, such as x-rays and gamma radia-
tion (higher frequency), passes through the organism with little absorption and
little killing action. Radiation at 253.7 nanometers is unique in its biocidal
action without objectionable heating or photochemical effects.

In practice, the radiations are generated by passage of an electric arc
through low pressure mercury vapor enclosed in a special glass that is capable
of transmitting 95% of the emitted light in the 253.7 nm band. To inhibit the
growth of organisms,an incident energy level in the range of 10^3 to 2×10^3 μW-
sec/cm^2 for yeasts and 5×10^3 to 1.3×10^5 μW-sec/cm^2 for mold spores is
required. Because the lamps are made in sizes equivalent to standard fluores-
cent tubes (with some modifications required in the ballasts), installations in
all classes of clean rooms and work areas are readily achievable. In use, the
lamps are to be used only when harm to the workers is impossible. Thus, pack-
aged components or rolls of the multilayer insulation material would be used in
light-tight boxes to lower spore counts at intervals. Times of use are before
bagging for storage in the assembly area, after removal, before mating,
and during off-hours of production of the full assembly. Standard practices of
the U.S. Health Service and the American Medical Association would be invoked
especially to screening, locking-out, and performing emergency treatments to
prevent accidental eye or erythemal effects. As recommended in Reference 7, all
bactericidal lamps would be checked periodically for ultraviolet output to make
certain that their biocidal effectiveness is maintained. Direct assaying of the
irradiated surfaces is required periodically to assure adequacy of treatments.

The lamps work most efficiently in still warm air so direct cooling of the
lamps would be precluded. A decrease in UV output of one-fourth to one-third
occurs if room temperatures drop from 80°F to 40°F. Some lamps are specially
made for air conditioning ducts and are suited to use in a laminar flow bench

installation. Because all assembly operations are contemplated for controlled temperature-humidity conditions, surface reductions in microbe count vary only as a function of distance from the lamp and focussing of all emitted energy by reflectance on a part or portion of the probe.

A secondary beneficial effect of standard bactericidal lamps is the production of ozone which in the presence of moisture serves as a bactericide and a fungicide. The lethal exposure of an organism is determined by its susceptibility, the wavelength of radiation, the density of radiant flux (watts/cm^2) and the time of exposure. Values for susceptibility for different bacillus and spores have been determined with an upper level in the order of 10^5 to 10^6 μW-sec/cm^2 ($\sim$1W-sec/cm^2) for a 90% (1 decade) destruction of virulent spores. Continued exposure produces additional decade reductions.

For example, if an open table top 6 ft x 8 ft is used and a standard lamp (G64T6) is centered 7 ft above, such that a 5 ft lamp axis is parallel to the 8 ft side (no point further away from the lamp than 7 1/2 ft), the 253.7 nm source produces an incident power density at any point 1 meter away of 150 μW/cm^2. Since energy density reduces as the square of the distance, a killing load of 30 μW/cm^2 will exist on the surface. A single decade reduction in microbe count results every 4400 sec (1.22 hr). If turned on after working hours (including plant maintenance periods) a 10 decade decrease is conceivable every night for all illuminated surfaces. Alternative utilizations include installation of lamps in laminar flow benches over its work surface or in the duct work. In the latter instance the microbial load of the air and dust remaining are continuously sterilized. An adaptation of this is a possibility of utilizing a heat generation laser to vaporize air-borne particles and microbes. UV irradiation is currently used in the sugar and bottling industries to keep materials and equipment sterile once this state has been achieved. In general, it is not practical to use the radiant energy to clean or decontaminate a dirty, greasy or sticky surface.

Synergistic Effects of Thermoradiation - The effectiveness of sterilization of a spacecraft has been shown by workers at the Sandia Laboratories to be enhanced by combined exposure to heat and radiation. Therefore, components prohibited from use because of unacceptable performance after protracted exposure to a temperature of 113°C (and 125°C for qualification tests) may be used because

durations are radically reduced. Exposure to gamma radiation does not of itself substitute one difficult environment for another because radiation hardening (so-called) must be exercised for probes entering the Jovian planets. The radiation level used in the sterilization procedure is moderate, 150 Krad.

The technique, as it evolved, employed a cobalt 60 source with collimated emissions directed at a rotating probe or component. For another spacecraft, a revetment at Kennedy Space Center would have been used to protect personnel while the spacecraft was turned on a table. The method, as described in Reference 9, had two difficulties which were not fully resolved. First, the entire activity had to be located near the launch site to minimize handling after sterilization. Second, the large Viking lander capsule made the job of heating and irradiating simultaneously difficult. A relatively inexpensive set-up was proposed whose cost was expected to be about $125,000 in 1970. A third drawback to adopting the procedure lay in the fact that the lander capsule might have to be sterilized at the fabricator's plant.

Many of the problems associated with its implementation relate to size. The probe is of a dimension that a hole in the floor or an oven-sized container can be built to provide the environment.

The benefits of the method are illustrated in Figure 11 which is drawn from Reference 10. Dry heat alone has a decade reduction time of D = 12 hours at this temperature (D = 5 hours for buried microbes at 125°C). When the same standard spore was sterilized at 11 krad/hr, a D-value of 7 hours was determined by test. The lower curve illustrates that when combined a synergistic inactivation occurs which is more than twice as effective as when the two are added together. The resultant value of D = 2.28 hours indicates a benefit at a temperature below boiling temperature that takes just 0.19 times the time to dry heat sterilize. Variations on the testing showed that the most effective temperature is about 105°C and that the stresses need to be applied simultaneously. The method appears to be feasible and practical, however, some testing of components is required in design and development phases to validate the method with actual hardware and to qualify the equipment. If the planet Saturn is proven to possess trapped radiation particles in numbers nearly equivalent to those of Jupiter, this type of radiant exposure will be a requirement for testing for radiation susceptibility of the equipment.

COMPARISON OF THE INACTIVATION OF BACILLUS SUBTILIS VAR. NIGER SPORES WITH GAMMA RADIATION, DRY HEAT AT 95°C, AND THERMORADIATION

RADIATION DOSE - krads
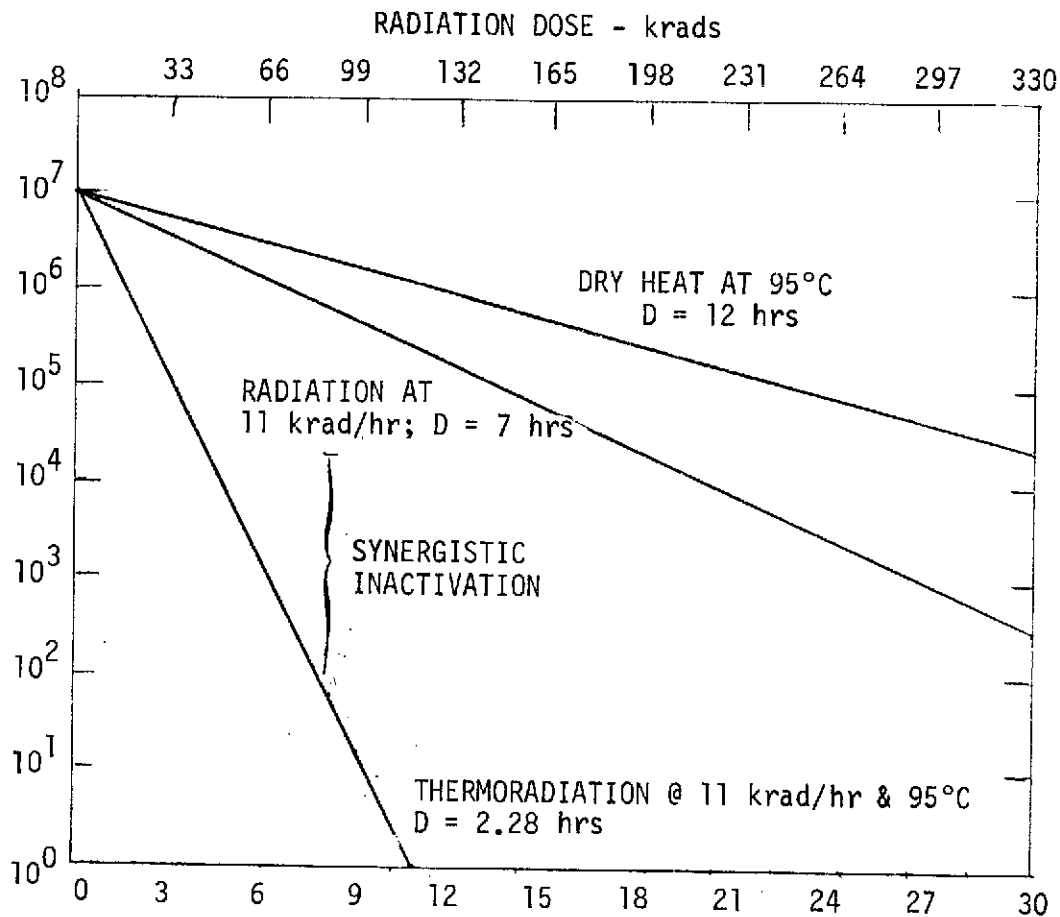
Figure 11

The probe can be designed to the stresses of heat sterilization alone; it could also be designed to the combined stresses of heat and radiation. Radiation alone is not advocated as a final sterilization cycle because the effects of long exposure are not known. Another aspect of the synergism is that heat is employed to anneal radiated parts; combining the two would assist in this annealing process.

Heat Shield Fabrication - The heat shield of the probe is made of an ablative material which deposits carbonaceous vapor and particles in the atmosphere during and just after peak heating. This contamination is initially so hot that no biological specimens trapped in it can survive. As the outer layer recedes, the inner material does rise in temperature but not instantly nor completely to auto sterilization temperatures. However, the high heat capacity of the known

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low molecular weight gases in their atmospheres, results in a very rapid de-
crease in surface temperature (down to 100-200°K) as subsonic velocities are
attained. If the cooling results in severe cracking from the gradients pro-
duced, some flaking or spalling can occur. For this reason the heat shield is
considered a potential or possible source of biological contamination, even
though bondline temperatures do climb to 600°F (800°F design).

The fabrication of the heat shields involve many heating cycles which gen-
erally range in temperature from 93°C to 177°C. This can kill the vegetative
microbes in an amount to about 90% of the total normal terrestrial loads. Full
credit cannot be taken, however, for the multiple heatings because of particul-
ate contamination caused by successive machinings after each assembly step.
The final curing can be considered as a partial component sterilization cycle
of the assembly because the bonding of the aluminum structural shell to the
honeycomb can be followed by bagging and desiccating to protect it from dust and
other nutrients. The 93°C shown in Figure 12 is a standard operating tempera-

SUAEP HEAT SHIELD FABRICATION PROCESSES

ENG. DRAWING (NO. & TITLE)	OPERATION	PROPOSED	ALTERNATE	COMMENTS
70A132010-FORWARD ABLATOR SUBASSEMBLY	(1) FABRICATE CARBON-PHENOLIC (MMS-516) HEATSHIELD & LAMINATES	10 HRS @ 163°C		
	(2) BOND C/P PIN TO C/P HEAT-SHIELD WITH HT-424 EPOXY-PHENOLIC ADHESIVE PER P.S. 14140	45 MIN. @ 93°C +90 MIN. @ 121°C +60 MIN. @ 149°C +60 MIN. @ 177°C	60 MIN. @ 177°C	
70A132040-FORWARD HEATSHIELD ASSEMBLY	(1) BOND PHENOLIC/GLASS (P/G) HONEYCOMB & P/G PRE-PREG TO C/P HEATSHIELD WITH HT-424 EPOXY-PHENOLIC ADHESIVE PER P.S. 14140. (NOTE 3 STATES TO MACHINE CORE AFTER BONDING-CONTAM. PROBLEM)	45 MIN. @ 93°C +90 MIN. @ 121°C +60 MIN. @ 149°C +60 MIN. @ 177°C 120 MIN. @ 93°C 120 MIN. @ 121°C 120 MIN. @ 149°C 120 MIN. @ 177°C 120 MIN. @ 204°C	[POST CURE]	POSSIBLY ELIMINATE MACHINING BY USING H/C PROCURED TO SIZE.
70A133001-PROBE STRUCTURE ASSEMBLY	(1) BOND WITH FM 123 PER P.S. 11308 (DRAWING CALL-OUT IN-ADEQUATE; -2 OR -5 MATERIAL) BOND FORWARD HEATSHIELD ASSEMBLY TO STRUCTURE	1 HR @ 107-132°C	"X" HOURS @ CURE TEMP.	ACCOMPLISH ONE STERILIZATION CYCLE BY EXTENDING TIME IN OVEN
70A133010-AFT HEATSHIELD ASSEMBLY	(1) BOND P/G HONEYCOMB & P/G PRE-PREG TOGETHER WITH HT-424 EPOXY-PHENOLIC ADHESIVE PER P.S. 14140. (2) APPLY ULD ELASTOMERIC ABLATOR & MACHINE TO FINAL CONTOUR (CONTAM. PROBLEM)	45 MIN. @ 93°C +90 MIN. @ 121°C +60 MIN. @ 149°C +60 MIN. @ 177°C + POST CURE 1 HR @ 93°C	"X" HOURS @ 110°C	PROCURE PRECUT H/C TO SIZE TO ELIMINATE MACHINING
70A138020-INSULATION INSTALLATION-INTERNAL	(1) BOND INTERNAL INSULATION WITH EC 2216 PER P.S. 11308, TYPE XIV	3-7 DAYS @ 25°C	60 MIN. @ 93°C OR HIGHER	
70A138041-AFT COVER INSULATION ASSEMBLY	(1) MAKE H402 FREON BLOWN FOAM PARTS (URETHANE) (2) BOND FOAM TO STRUCTURE WITH EC 2216 PER P.S. 11308, TYPE XIV	ROOM TEMP. (25°C) 3-7 DAYS @ 25°C	60 MIN. @ 93°C OR HIGHER	

Figure 12

ture in current manufacturing practice. It is not an upper bound; the cure temperature can be elevated to 105°C or 110°C thereby making it fully usable in specifying quarantine requirements. Again, cleanliness after the heat cycles is of paramount importance in these procedures.

The assembly steps for the fore and aft heat shields are explained diagrammatically in Figures 13 and 14. This particular assembly plays the prime role in preventing biological contamination in the planetary atmospheres, therefore, final producibility engineering must place top emphasis on strength after exposure to peak heating and on processing that promotes self-sterilization.

PROBE FORWARD HEAT SHIELD ASSEMBLY

Figure 13

AFT HEATSHIELD

FABRICATE PHENOLIC-GLASS (P/G) HONEYCOMB AND LAMINATE ASSEMBLY 70A133010 PER P.S. 14140	→	BOND ABLATIVE HONEYCOMB (H/C) TO P/G STRUCTURE AND POST CURE ASSEMBLY	→	FILL H/C WITH ELAST-OMERIC ABLATION MAT'L AND MACHINE TO FINAL DIMENSIONS

ELASTOMERIC ABLATOR

HT-424 FILM ADHESIVE

FIBERGLASS LAMINATE

PHENOLIC-GLASS HONEYCOMB
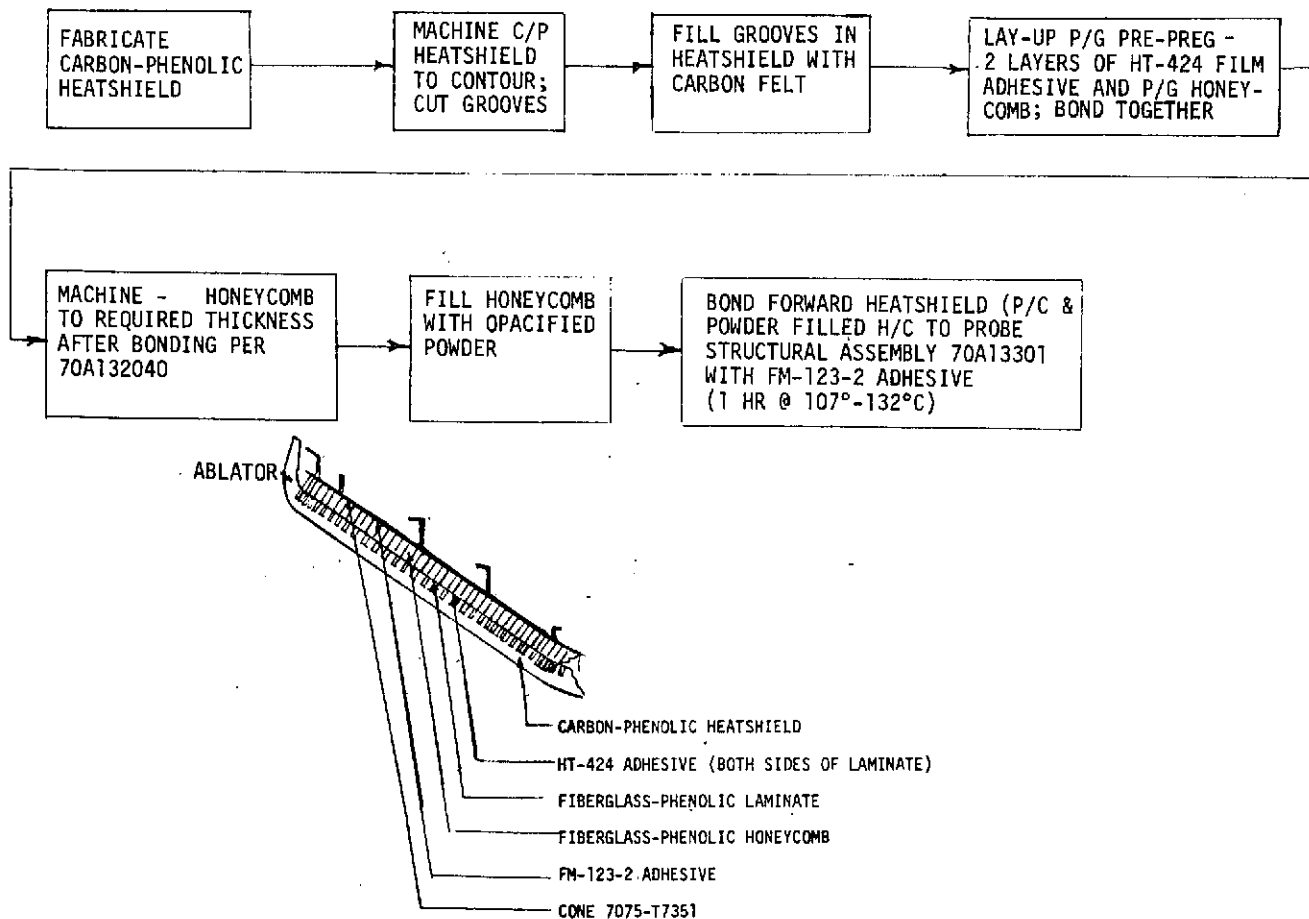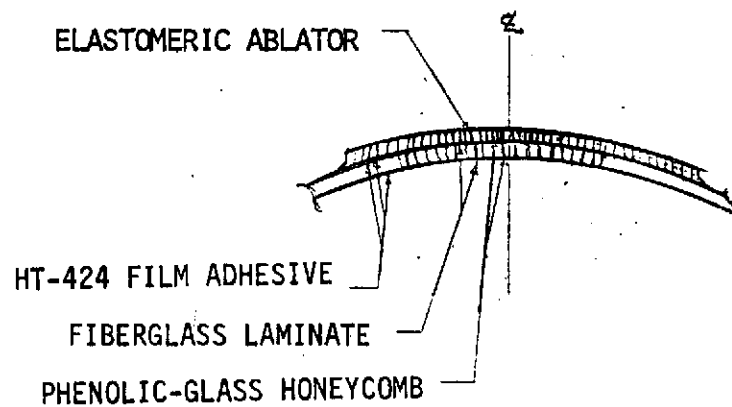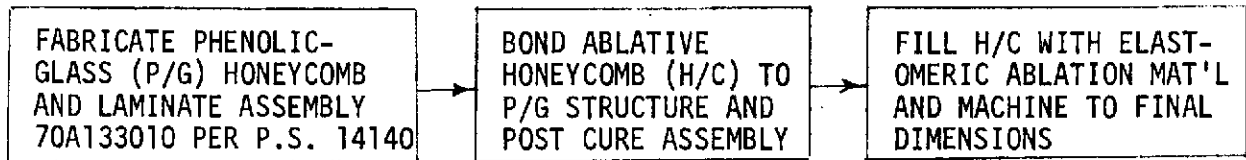
Figure 14

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ENTRY CONTAMINATION MECHANISMS

A probe mission to be successful in the atmospheric descent must be targeted at the aim point that produces a predictable environment. The planet's high rotation speeds aid in reducing relative velocity and decelerations. The entry corridor must be of a size that the aim point plus 3σ uncertainties fall within the corridor. The corridor is bounded by the extremes in atmospheric models and the entry angles anticipated. The first is arbitrarily defined based on our limited knowledge of the gross planetary abundances and postulated diurnal conditions; the second is independently selected after consideration of scientific objectives, transit vehicle limitations, and probe design capabilities.

The corridors for which this probe is designed are presented in Figure 15. Note that the probe is structurally designed to survive entry when deceleration loads are less than 800 g_E's. (A 5σ structure $\approx 1000 g_E$ ultimate loading).

o   For Jupiter g_{max} <1000 when γ <-14° for all currently defined atmospheres (including A. J. Kliore's definition based on Pioneer 10 occultations).

o   For Saturn and Uranus g_{max} <1000 for γ_S < -52° and γ_U < -67° in the NASA Cool Model atmospheres.

The probe will fail structurally in Cool atmospheres at all angles steeper than those defined. For entries into Nominal and Warm Models g_{max} < 1000 at all entry path angles up to vertical entry. Failure due to excessive g-forces can produce biological contamination if the interior bioburden is high and the debris does not burn up. Metallic items will melt but ablator protected metal components probably will not.

Growth and replication are dependent on the requirements itemized by Taylor, et. al. in Reference 5. The nutritional requirements of bacteria is quoted in the reference as divided into 4 categories: (1) carbon source, (2) energy source, (3) salts, and (4) water. The authors' evaluation indicate that of all outer planets and satellites the highest probability (not quantified) of growth exists in Saturn's atmosphere with Jupiter having a lower likelihood. The differentiation is based on availability of liquid water and relatively high concentrations of nutrients. Titan is ranked next and all other satellites are ranked very low in growth potential. Uranus was not ranked but a cursory examination indicates a

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low probability based on the lower probability of encountering water, ammonia and carbonaceous compounds at Uranus. In general, the relative abundance of these compounds is about one-fourth that of Saturn. Because of its distance from the sun, the energy available also is about one-fourth that at Saturn's radius. Thus, the potential for life-support appears to be highest at Saturn with Jupiter, Titan and Uranus following it in precedence.
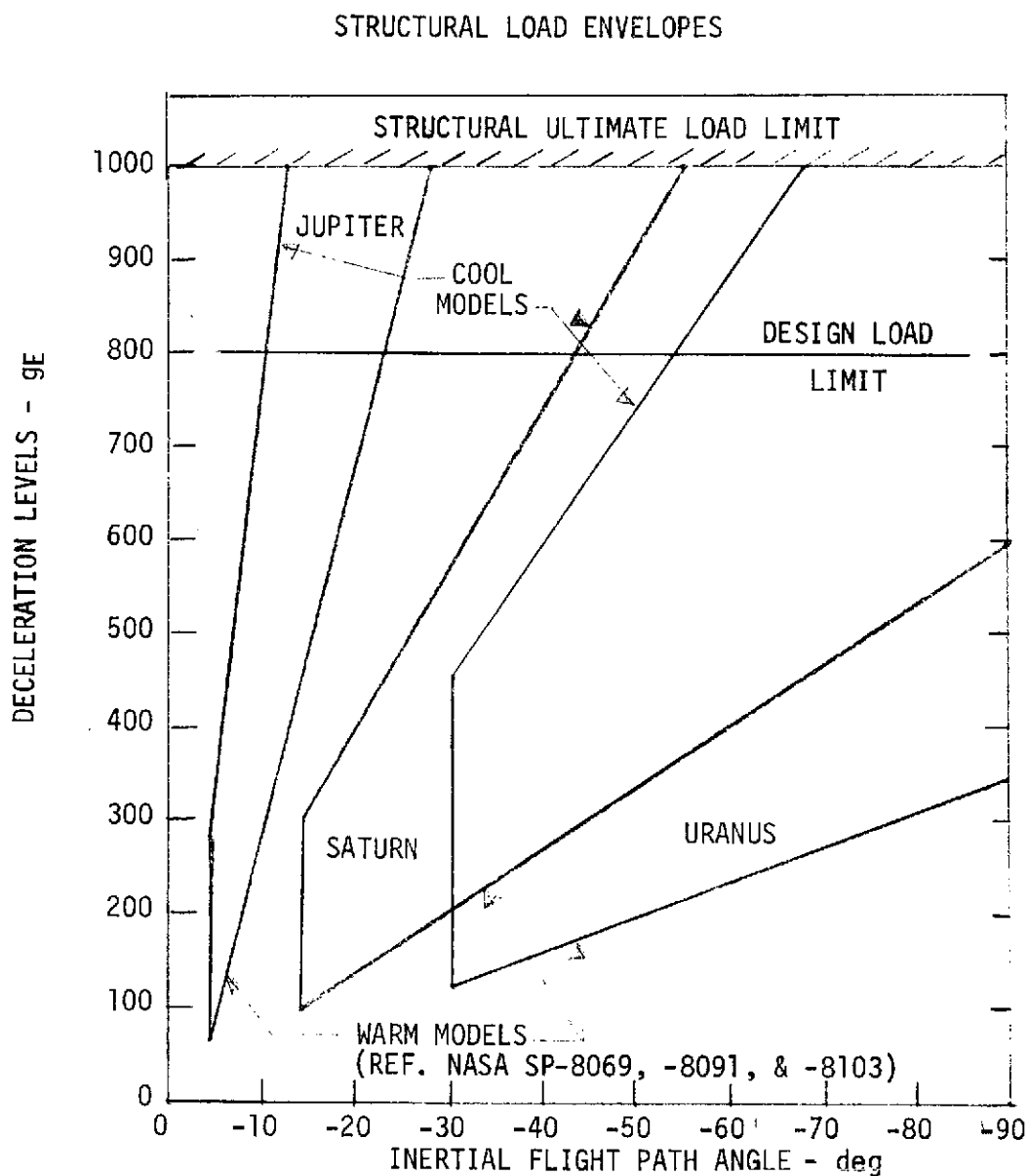
STRUCTURAL LOAD ENVELOPES

Figure 15

Another aspect of Uranus as a target planet that must be weighed is the currently large ephemeris uncertainties. Reference 1 states that these errors cause 3σ variations in entry angle of $\pm15.85°$. Thus, a Uranus aim limitation of $-37°$ would have to be imposed to prevent exceeding the 800 g_E design limit by entry dispersions.

Survivability Boundary

Analyses by Swenson, Reference 11, showed that for a given material specific heat capacity, shock layer radiative heating completely could destroy large bodies while convective heating from the boundary layer can destroy small bodies. The degree of overlap from these two destructive heating mechanisms depends primarily upon the heat capacity of the body material and entry flight path angle. Swenson, in Reference 11 has defined sizes of survival based on specific heat capacity and body gravity of the falling object. The survival range for ablator covered probes is in the range of 7 to 30 MJ/kg with a radius of the order of 0.5 to 1 m and specific gravity of 0.2. The entry probe for Saturn/Uranus entry has a 45 cm radius and a specific gravity that varies from 0.45 to 0.42 as it ablates (a Jupiter probe would vary from 0.66 to 0.44). The probes have a major diameter of 0.89 m so they appear to fall just outside of the survivability region defined in Reference 11, Figure 6 for Jupiter entries. The heat capacity of this probe is calculated to be 28.5 MJ/kg at 3900°K, the predicted peak temperature for a Uranus cool entry. The crossmark in Figure 16 shows the locus of the SUAEP relative to the Swenson definitions. The design is therefore marginal and will require extensive testing to assure thermal integrity.

In Saturn or Uranus entries the relative amounts of radiative to total heat flux are illustrated in Figure 17. The planetary heat pulses are characterized in all cases with high radiative heat fluxes. The magnitude actually encountered is strongly influenced by the initial entry angle and the real atmospheric characteristics. In the analytical process the steep entries into Saturn and Uranus cool atmospheres approximate the peak flux generated in a Jupiter Nominal atmosphere model at an angle of $-7.5°$. However, the total heat input in Jupiter is greater even though a low angle is planned.

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PROBE SURVIVABILITY

FAILURE ANALYSIS

SOURCE	MODE	SOLUTION
o PROBE OUTSIDE DESIGN BOUNDARIES	o STRUCTURAL FAILS; PROBE UNSTABLE	o WIDEN BOUNDARIES; INCREASE STRENGTH
o UNCERTAINTY IN HEATING OR DEGRADED PERFORMANCE OF HEAT SHIELD	o HEAT SHIELD UNBONDS; SHIELD BREAKS AWAY	o ADD MATERIAL TO RAISE MARGIN OF SAFETY
o PROBE STRUCTURE HEATS UP DEEP IN ATMOSPHERE	o ALUMINUM MELTS; STRUCTURE COLLAPSES	o SUBSTITUTE TITANIUM
o PIECES OF MLI SURVIVE ENTRY	o MLI ON AFTERBODY PROTECTED DURING PEAK HEATING	o REDESIGN INSULATION ON AFTERBODY

SURVIVABILITY BOUNDARY - JUPITER

AVERAGE BODY SPECIFIC GRAVITY = 0.5
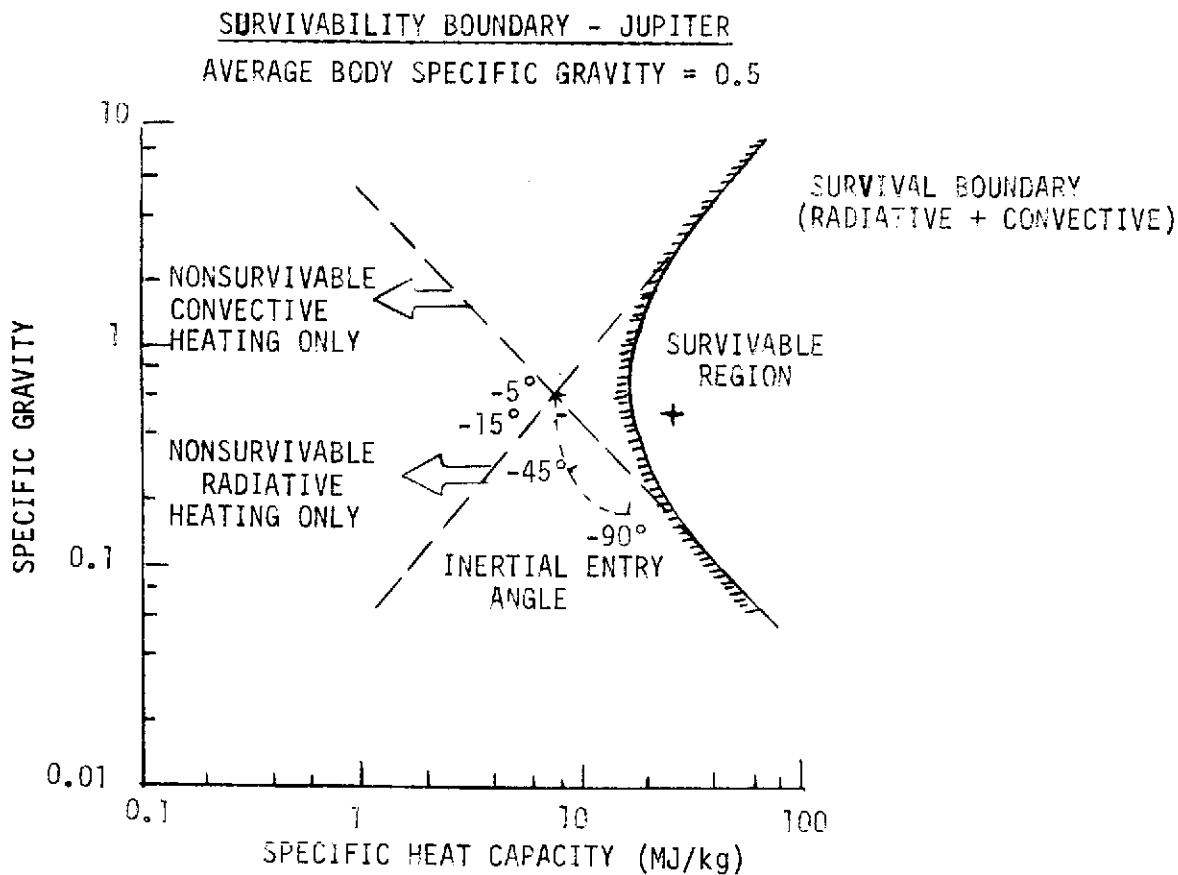
Figure 16

TOTAL HEAT FLUXES IN TYPICAL PLANETARY ENTRIES

- NO BLOWING
- STAGNATION POINT

SHALLOW – JUPITER
NOMINAL ATMOSPHERE
γ_I = –7.5°
V_R = 47.4 km/sec

STEEP – URANUS
COOL ATMOSPHERE
γ_I = –50°
V_R = 26.3 km/sec

STEEP – SATURN
COOL ATMOSPHERE
γ_I = –40°
V_R = 30.4 km/sec

TOTAL HEAT
Btu/ft^2 – sec

HEAT FLUX – 10^3 Btu/ft^2 – sec

Q_T = 336,500

Q_R = 190,000

TIME FROM ENTRY, t_E – sec

Q_T = 95,000

Q_R = 64,000

TIME FROM ENTRY – sec

Q_T = 63,500

Q_R = 26,500

TIME FROM ENTRY – sec
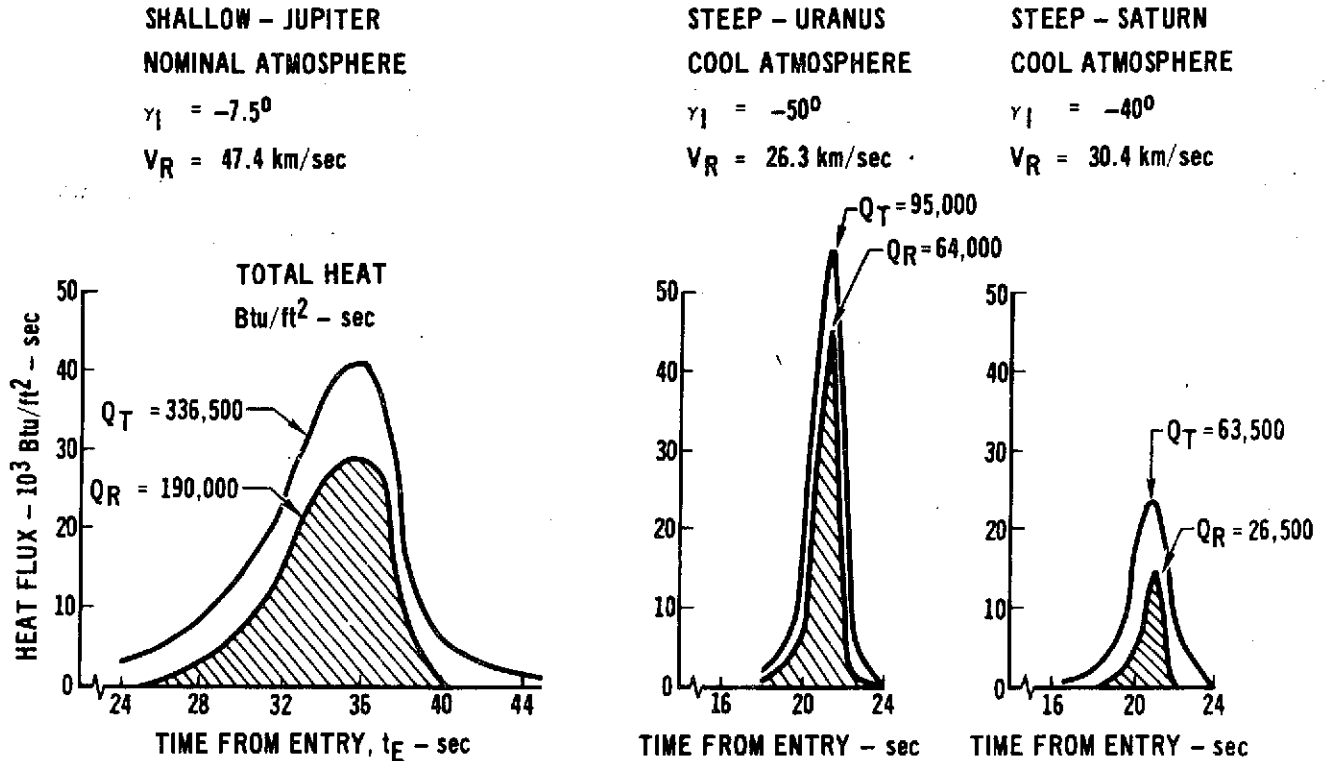
Figure 17

The high heating rate for Uranus is due to the large proportion of helium specified in the control document (Reference 12). The large helium to-hydrogen ratio (60:31 for the Cool model) cause high deceleration loads, stagnation pressures, shock layer temperatures, and thermal radiation fluxes. The integrity of the carbon phenolic at the heat fluxes and temperatures (up to 4000°K) have yet to be validated in simulated environments but modeling and sizing studies do attest to the feasibility of the ablative material to survive if the design entry envelope is met. The steepest angles are selected to limit maximum deceleration in the worst atmosphere model to 800 g_E (limit load) which yields a 1000 g_E ultimate load capability (factor of safety = 1.25). The entry corridors for Jupiter, Saturn and Uranus are defined in Figure 15.

Multilayer Insulation Contamination

The materials most apt to proliferate debris in a planet's atmosphere are
the multiple layers of mylar and nylon net used to inhibit radiant heat loss
during transit and descent to atmosphere encounter. A failure mechanism of
peeling and tearing is postulated. The precise nature of these flakes is
difficult to predict. A worst-case analysis is shown in Figure 18. The
maximum heat flux due to convection is for single sheets of mylar falling through
Saturn's atmosphere. Being very thin ($\sim$.004 in.) the torn sheets of plastic
have very small heat capacity so they will self-sterilize.

MYLAR MLI HEAT ANALYSIS

WORST CASE:
VELOCITY PERPENDICULAR

A) FLAT PLATE   B) TEAR DROP   C) EDGEWISE
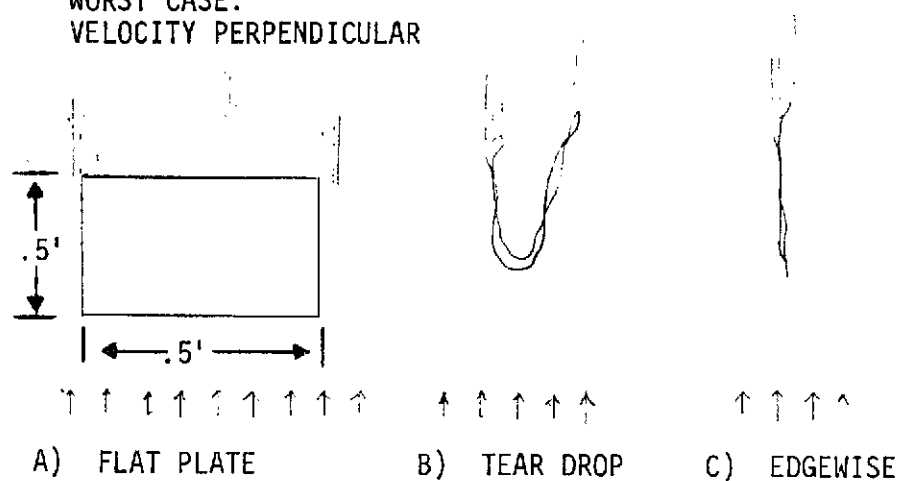
Figure 18

Mylar density is high compared to that of an integral probe. The result
is that a piece of mylar would be subjected to similar heat fluxes during high
altitude descent. Since mylar melts at temperatures below 600°F (See Figure 19)
its penetration to the life zone is unlikely. If it does not melt the surfaces
will have been heated to temperatures that sterilize in seconds. Thus, even
though destruction is not readily provable except by extensive tunnel
and free-fall tests, survival of the material is considered to be a low
probability.

SURVIVAL OF MLI LAYERS DURING ENTRY

SATURN ENTRIES

4000

COOL ATMOSPHERE

EQUILIBRIUM TEMPERATURE - °F

3000

MLI LAYER
6" X 6" x .00025"

$M/C_D A = .006 \ gm/cm^2$

V

2000

WARM ATMOSPHERE

1000

MYLAR MELT TEMPERATURE

0

0   20   40   60   80

ENTRY ANGLE - DEGREES
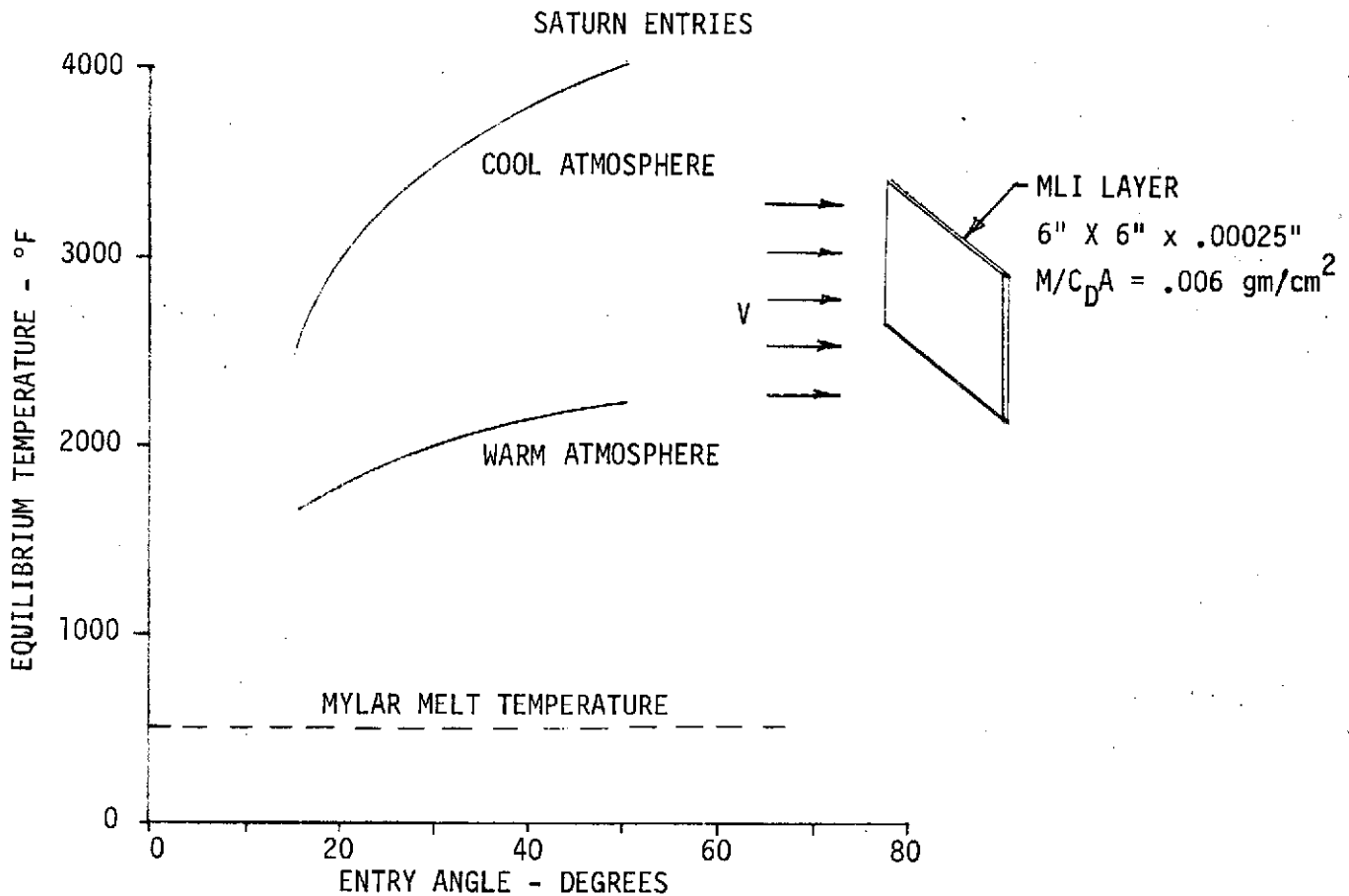
Figure 19

Falling in other than a flat plate shape such as on edge or in a folded or teardrop configuration increase $M/C_D A$ further which cause peak heat flux, $\dot{q}$, to be encountered at a lower altitude where ρ_{atm} is higher. The result is that a flat plate assumption yields the best potential for survival to the life zone.

Chunking or particle release down to the particle dimensions defined by Gonzalez, et. al. in Reference 13 indicate that minute particles of the order of 1 to 30 μ can survive Jovian entry for low angle, low peak heat flux conditions. The possibility that these particles will retain viable organisms has not been proven. With Taylor's work the probability of growth requires survival to the life zone, freedom from high altitude ultraviolet irradiation, and a source of moisture and other nutritional compounds.

Ablative Material

The sterility of the ablative material is discussed under Minimization
of Microbial Load. Break-off or spallation of carbon phenolic or silicone
materials may occur after peak deceleration as a result of rapid cooling in
cool, hydrogen rich atmospheres. The severity of such break-up is unknown but
design analysis and testing under simulated entry conditions is imperative
to prevent excessive spallation. Descent stability is adversely affected by
holes, especially holes that penetrate the inner surface. The chunks and particles,
however, can be made free from biology by prelaunch heating and bagging.

Internal Microbe Loads

This analysis has determined that probe internal microbial loads are a non-
contaminator if structural integrity is retained down to temperature levels
where melting of the aluminum structure occurs. In satellite descents,
on the other hand, impact with a liquid or solid surface may precipitate
break up. Analysis of this release mechanism is beyond the scope of this study.

Probe Sensor Ports

The probe structure is a vented structure to permit continuous pressure
equalization during ascent form Earth and descent into the target planet. The
mating surfaces approximate a semi-sealed condition to inhibit massive entry
of gases which would create a destabilizing force, increase convective heat
transfer, and permit scouring action by the gases of internal surfaces. The
latter process is biologically contaminating owing to escaping and mixing
during the spinning descent. Because of this the sensor ports must be treated
prior to launch to absolutely minimize terrestrial contaminants.

There are 6 openings to be treated as seen in Figure 20. The neutral
mass spectrometer sampling tube and exhaust port are considered to be non-
contaminating because it is a sealed, evacuated instrument at launch and
remains so throughout transit. When the instrument is deployed (and uncapped)
the probe is in a subsonic descent mode. Also, the probe is still revolving
around its axis of symmetry with a predicted oscillation of 10° or less.

PROBE SENSOR PORT LOCATIONS
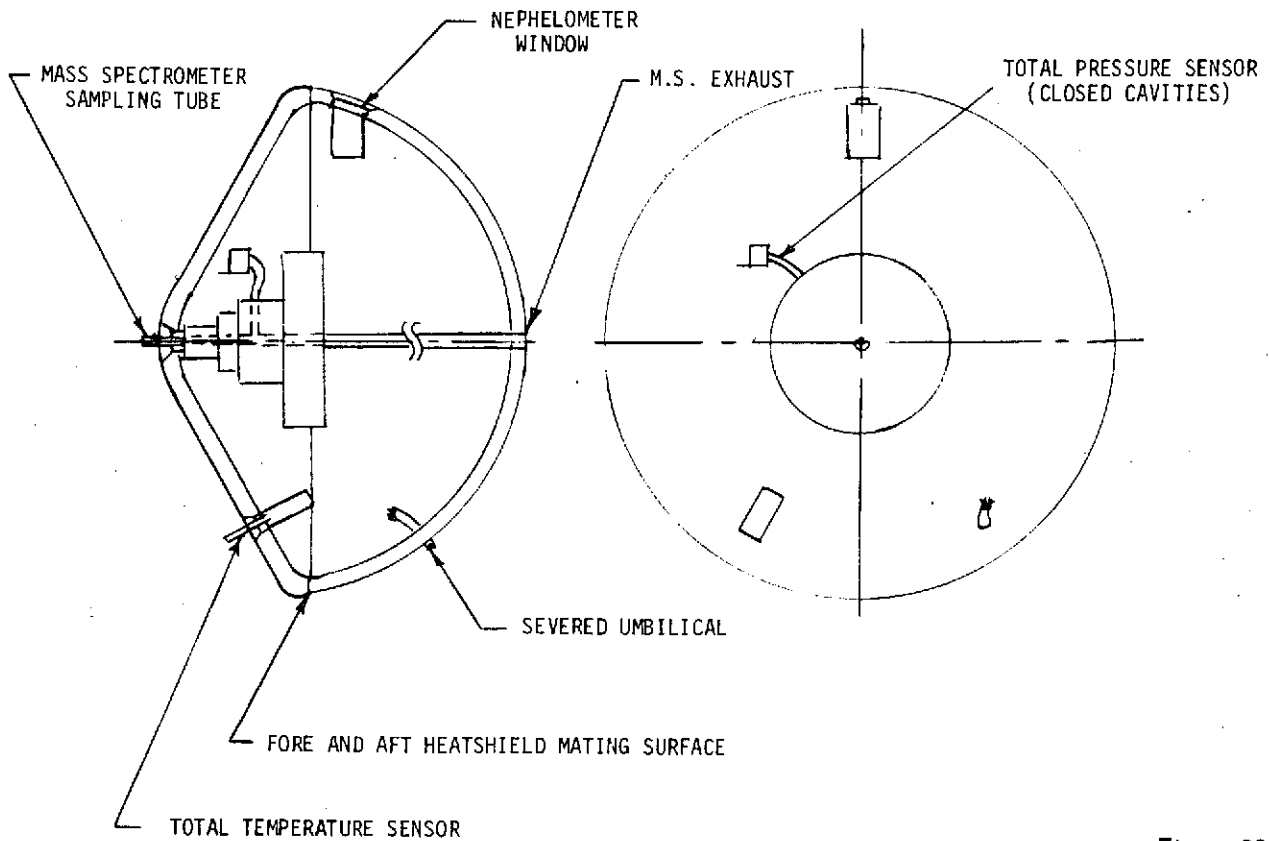
Figure 20

Thus, the tube tracks the stagnation point and the exit is diametrically opposed. Both conditions tend to minimize particulate contamination upon which biology is dependent. The tube is sealed to preclude flow into the equipment compartment and the pressure sensor consists of four closed cavities which improve accuracy in a variable pressure environment ($\sim$ four orders of magnitude change). The combined tubing network is carefully sealed to assure accuracy of measurement. This prevents intermingling of gases between the innards of the instruments and the cavity inside the forward heat shield.

Similarly, the temperature probe, nephelometer, and radiometer/photometer instrument either deploy through self-sealing openings or have closed openings even when the ablative cover port is ejected. The severed umbilical cable remains as a stub. A suitable ablative, wire insulation specified guarantee that it will not melt away to a level below the inner surface.

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It too is sealed round about its opening with a grommet. There are three other depressions in the back cover for probe/spacecraft mounting. All attachments can be into blind holes to assure that no passage exists.

The principal macroscopic opening is the parting line between heat shields. This opening will be carefully engineered but without a sealing ring. The primary criterion is prevention of cracking of either ablator or supporting honeycomb structure caused by differing expansion characteristics.

The treatment of the closing ports and emplaced seals requires cleanliness and extinction of spores and vegetatives prior to final insertion. If a contaminating condition at any port is experienced, corrective action of a local nature is to be carried out. The form probably will be subject to manufacturing-engineering-quality control-planetary quarantine control action similar to that involved in all Material Review Board actions. The specific action taken will have to be a previously approved technique, but implementation has to be evaluated contemporarily.

COST SAVINGS

Schedule Effects - The cost estimates of Reference 1 were based on the imposition of heat sterilization techniques for controlling microbe counts to launch. Some reduction in development costs were estimated because of inheritance from Viking, specifically, in use of NASA Approved Parts Lists for electronics and instruments. In general, some level-of-effort staffing increase to sustaining personnel in the microbiological assay and monitor functions along with some particular additions and changes in components. The impact on schedule was considered to be zero to slight.

All aspects of engineering, procurement, manufacturing, and operations were reviewed to determine total impact. Figure 21 shows some of the key effects that can be anticipated if heat sterilization is specified, especially if multiple sterilization cycles are adopted to insure low counts. The effects are an average increase in any one activity of 1.5 months to a base estimate of 8.2 months. This represents an 18% increase in direct manhours in probe assembly and delivery. The remainder of increased cost is accountable to all components. Another effect of the increase in time is a need for moving the authority to proceed (ATP) forward one month (results from 1.1 month general shift).

The schedule impact of increased dependence on cleanliness alone will materially shorten the development time. Study of Alternative I indicates that the average increase can be held to about one month. Study of Alternative II indicates no stretchout in program time. The reduction in costs with these two levels of cleanliness are discussed below in the treatment of costs.

Cost Impacts
The estimate of 21% in Reference 1 ($8.3 million compared to $39.6 million) precipitated a strong interest in the study of alternative techniques that could fulfill the planetary quarantine objectives with distinct cost advantages. The first alternative consists of implementation of a Class 100 room (no more than 100 particles 5 microns or larger per cubic foot) combined with an antibioload (antiseptic) treatment to remove residual or accidentally large counts (see Figure 22, Alternate I).

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OUTER PLANETS PROBE SUMMARY PROGRAM SCHEDULE

(INCLUDES P.O.)

SCHEDULE NO.	CALENDAR YEARS	1975	1976	1977	1978	1979

Row labels (left column):
- PROGRAM MILESTONES
- PHASE B CONCEPT DEFINITION
- PHASE C/D DEVELOPMENT OPERATIONS
- DESIGN
- SYSTEM REQUIREMENTS
- SUBSYSTEM PROCUREMENT
- GFE REQUIREMENTS (SCIENCE INSTR)
- TOOLING/DETAIL PARTS FAB
- HEATSHIELD FAB & ASSEMBLY
- STR. TEST ARTICLES FAB & ASSEMBLY
- PROOF TEST UNIT FAB & ASSEMBLY
- FLIGHT ARTICLE FAB & ASSEMBLY
- DELIVERIES
- TESTING
- PTU - TESTING
- OPERATIONS
- GSE
- FACILITIES
- CLASS 100 ROOM

Milestones and annotations:
- Ø B RFP, Ø B PROPOSAL, Ø B ATP, Ø C/D ATP, PDR, CDR, SN-1 LAUNCH
- HT. SHIELD TESTS, AERODYN DROP TST.
- CONCEPT FREEZE, SN-1 DELIVERY
- 10%, 90% STR. DWG. REL.
- MISSION REQ., PRELIM. CEI & ICD, FINAL CEI, FINAL ICD
- INT. P.O., INT. ESTU UNIT, INT. QUAL. UNIT, INT. PTU UNIT, INT. FLT. UNIT
- INT. ESTU UNIT, INT. PTU UNIT, INT. FLT. UNIT
- STVU, PTU, SN-1, 2, 3
- ESTU, DMM, STVU
- SN-4
- SN-1, 2, 3
- SN-1, 2, 3, 4
- START ESTU TSTS, STR. DYNAM. TSTS, STR/THERM VAC. TST, ULTIMATE LOADS
- DEL. PTU TO KSC, TO NASA, RTN TO MDAC-E
- SN-1 REC & INSP, MATED FLT S/C-PROBE C/O, SN-1 LAUNCH
- FACTORY TST. EQUIP., COOLING UNITS, MATING & TST FIXTURE AT KSC
- FACTORY, RHU STORAGE & ACCTG.
- ST. L.

Legend:
- ◇ = NASA
- ▽ = MDAC-E
- ○ = P.O.'S
- ◊ = ESTU HRDWR REQ'D
- ◈ = VNDR. QUAL. HRDWR
- △ = FLT. HRDWR REQ'D
- ═ = MDAC-E ACTIVITY
- ▩ = NASA ACTIVITY
- ▬ = S/C CNTR ACTIVITY
- /// = PTU REFURBISHED TO S/N-4 PROBE

PREPARED BY	CALENDAR MONTHS	1975	1976	1977	1978	1979

COMPARISON OF COSTS - ALTERNATIVES I & II

(10³ 1973 Dollars)

Alternate I   Class 100 Room + Final (1) Heat Cycle

Subsystem	Design & Analysis	Dev Test Program	Flight Hardware [1]	Mission Support [1]	Total Program
Structure	$ 89	$ 480	$ 155	--	$ 725
Heat Shield	--	38	--	--	38
Power & Distribution	124	139	169	--	431
Telecommunications	--	382	377	--	759
Mission/Aero Analysis	--	5	4	--	9
Thermal Control	--	18	15	--	34
Pyrotechnics	149	22	15	--	187
Inst-Engineering	--	9	8	--	17
Inst-Scientific[2]	--	13	8	--	21
System Integration	139	400	605	$553	1697
Reliability	13	--	--	--	13
Tooling	78	4	188	--	269
GSE	250	18	8	--	276
Program Management	38	21	12	33	103
Operations & Control	14	34	26	--	73
Totals	$893	$1582	$1592	$585	$4652

Alternate II   Class 100,000 Room + UV Irradiation

Subsystem	Design & Analysis	Dev Test Program	Flight Hardware [1]	Mission Support [1]	Total Program
Structure	--	$ 321	$ 86	$ --	$ 407
Heat Shield	--	25	--	--	25
Power & Distribution	--	109	120	--	229
Tlecommunications	--	194	189	--	383
Mission/Aero Analysis	--	2	2	--	5
Thermal Control	--	10	8	--	17
Pyrotechnics	--	12	8	--	20
Inst-Engineering	--	5	4	--	10
Inst-Scientific[2]	--	9	4	--	13
System Integration	$130	203	400	553	1285
Reliability	17	--	--	--	17
Tooling	--	--	--	--	--
GSE	179	--	7	--	185
Program Management	12	14	12	32	70
Operations & Control	11	37	13	--	60
Totals	$348	$942	$852	$585	$2727

(1) 4 Flight Units, 3 flights
(2) CFE Science Instruments

Figure 22

A pilot operation of a Class 100 room in which personal hygeine, representative fabrication and troubleshooting work, and careful accounting of expended time and dollars has shown feasibility. The work was carried out to compare cleanliness with documented heat sterilization procedures; it is described in Reference 14.

In the second alternative Class 100,000 rooms (the same standard per Reference 15 but 100,000 particles rather than 100) would be the site for virtually all operations. When manufacturing operations dictate departure from the confines of a Class 100,000 room some antibioload procedure is imposed to transfer it back. A careful selection of techniques is to be made prior to Phase C/D to choose among the various features:

Installation Cost (nonrecurring)
Deactivation Effectiveness (kill capability)
Performance Reductions
Schedule - Operations Impacts (recurring costs)
Life Shortening Effects

In all three cases a principal cost impact is that associated with additional handling and record keeping to assure accountability and traceability of parts, components and the assembly. This type of expense can be minimized by combining the data to be gathered with traditional quality assurance, reliability and maintainability records. All have a bearing on mission accomplishment.

The results of the two alternative cost analyses are displayed in Figure 22 with the significant features of each summarized in Figure 23. The successive cost reductions from $8.3 million to $4.6 to $2.9 million, though preliminary in nature, represent realistic magnitudes and ratios. The latter cost increments amount to 12% and 7%, respectively, of direct probe costs. The original $8.3 million increment has been estimated to represent about a 6% addition to overall costs. The ratio of planetary quarantine to overall cost would obtain in all three cases.

The cost data breakdowns are similar to previously submitted data, however, some regrouping has been effected to simplify the matrix. Thus, all Mission Support, which is basically time and material to support launch and

FEATURES OF PLANETARY QUARANTINE CONCEPTS

HEAT STERILIZATION (113° FOR TBD HOURS)	ALTERNATE I (CLASS 100 ROOM)	ALTERNATE II (CLASS 100,000 ROOM)
o TERMINAL STERILIZATION CYCLE (113°C FOR UP TO 54 (HRS)	o CONTROLLED CLEANLINESS IN ALL ASSEMBLY STEPS (CLASS 100 ROOM/LAMINAR FLOW)	o CLEANLINESS EXERCISED IN STANDARD COMPONENT AND ASSEMBLY AREAS (CLASS 100,000 ROOM; RESTRICTED ZONES)
o MULTIPLE BIOLOAD REDUCTIONS (1 TO 8 POSSIBLE)	o CORRECTIVE STERILIZATION (WHEN NEEDED) (3)	o NIGHT TIME UV IRRADIATION
o SPORE ASSAYING AND ESTIMATING	o FREQUENT ROOM AND PART ASSAYS FOR BIOLOAD	o LAMINAR FLOW BENCH UTILIZATION
o NASA APPROVED PARTS LIST COMPONENTS-OR-QUALIFY TO MEET TEMPERATURES	o PROTECTIVE COVER REQUIRED (4)	o ROUTINE ROOM AND PART ASSAYS; CORRECTIVE ACTIONS, AS NEEDED (3)
o BIOSHIELD REQUIRED (1)	o BATTERY SPECIALLY DESIGNED (5)	o PROTECTIVE COVER REQUIRED (4)
o BATTERY AND WIRING SPECIALLY DESIGNED (2)	o NIGHTTIME ULTRAVIOLET IRRADIATION	o BATTERY SPECIALLY DESIGNED (5)
o FULL PARTS CONTROL AND TRACEABILITY (6)	o FULL PARTS CONTROL AND TRACEABILITY (6)	o FULL PARTS CONTROL AND TRACEABILITY (6)

(1) BIOSHIELD LAUNCHED; COVER JETTISONED AT INSERTION
(2) STERILIZABLE BATTERY; HIGH TEMPERATURE WIRING
(3) PHENOL WIPING; ETHYLENE OXIDE IN DIMETHYL SULFOXIDE; OR UV IRRADIATION OF PARTS BEFORE ASSEMBLY

(4) COVER FOR GROUND OPERATIONS; COVER OMITTED AT S/C-PROBE STACKING
(5) STERILIZABLE BATTERY ADVISABLE TO REDUCE PROGRAM RISK ESPECIALLY FOR SATURN & TITAN
(6) STANDARD PRACTICE AUGMENTED WITH CLEANLINESS (AND STERILIZATION CYCLING)

Figure 23

mission operations, has been grouped as integration or management functions. It has apparently increased because some flight hardware costs were moved in the cost estimating relationships. Other minor internal costing changes have resulted from other changes in internal accountability.

The Design and Analysis functions are the most significantly affected in both alternatives. Development Testing and Flight Hardware costs decrease because there is no hard and fast requirement for a bioshield or extensive improvements in the power supply. As in previous costing exercises four flight units were assumed, the fourth of which is an upgraded Proof Test Unit, and all instruments are engineered and procured directly by the Contractor. If either assumption is changed, the overall numbers could decrease.

It is concluded that lower cost alternatives are available, but a cautionary note is required that some validation testing of the effectiveness of cleanliness, assaying, and correctional sterilizing is needed prior to determination of final drawing releases and firm cost estimations (Phase C/D, Development and Operations).

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ACKNOWLEDGEMENTS

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DEFINITIONS

Terms

Ablative	A material that absorbs heat by decomposition to gases.
Allocation	An allowable probability of contamination, established by NASA (see Reference 3)
Autosterilization	An integrated (temperature-time) relationship that assure kill.
Bioload, bioburden	The microbial burden estimated to be on a spacecraft or component
Class XXX	Cleanliness criteria (see Reference 15)
Cure	A fabrication procedure for completing phenolic linkages in ablative materials
Epoxy	A strong plastic resin
Freon	A trade name for flurocarbons
Heat-irradiation	Combined dry heat and γ-ray exposure
Life Zone	A temperature-altitude region of the planetary atmosphere that can support vegetatives
Midcourse Maneuver	A spacecraft control action to improve targeting
Penetrant	A liquid that promotes penetration into cracks and crevices.
Spalling	A mechanism of erosion (beyond ablation)
Spore	A dormant form of a bacterial (vegetative) cell
Survival-Microbe	Ability of terrestrial biology to enter outer planet alive and able to proliferate
-Probe	Ability of probe to enter without catastrophic failure
Vegetatives	The evolved cell which proliferates

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Notation

A	Angstrom unit (10 nanometers)
C/D	Phase designation - Execution
CFE	Contractor Furnished Equipment
COSPAR	Committee of Space Research
$\mathcal{C}$	Centerline
D	Decade reduction time (logarithmic kill rate)
g_E	Earth gravity (980 cm/sec^2)
GSE	Ground Support Equipment
H/C	Honeycomb (herein: phenolic filled fiber glass)
HT-424	A trade name designation of an adhesive
kg	Kilogram
KSC	Kennedy Space Center
krad	Kilorad of radiant energy
$M/C_D A$	Ballistic coefficient (gm/cm^2)
MLI	Multi-layer insulation (mylar and nets)
M.S.	Mass spectrometer
n	Number
P	Probability value (subscripts defined where introduced) Pressure (atm)
$\dot{q}$	Heat flux (Btu/ft^2-sec)
Q	Total heat input (Btu/ft^2)
S/C	Spacecraft
SUAEP	Saturn/Uranus Atmospheric Entry Probe
T	Temperature (deg C, F and K)
TBD	To be determined

Notation
(cont.)

TSC   Terminal Sterilization Cycle

ULD   A trade name designation for a silicone material

UV   Ultraviolet

γ Magetism (10^{-5} gauss)
              High frequency (10^{20} Hz) electromagnetic wave (10^{-1} to
                 10-2 MeV)
              Entry angle at a selected altitude (usually 450 Km)

ρ Density (gm/cm^3)

σ A measure of standard deviation

APPENDIX A
COMPARABLE SPACECRAFT CONTAMINATION LEVELS

Several other spacecraft have been checked for microbial load as part of the development of quarantine procedures. Up until the Viking program all forms of microbes were monitored to acquire adequate statistics on the form and counts extant. The relative amounts are illustrated in the table for the Pioneer F and G (10 and 11) Jupiter-bound spacecraft.

TABLE A-1
Pioneer F and G Microbial Estimates ($A_{total} = 63 \text{ m}^2$)

Spacecraft	Species	Type	Count (n/m²)
F	Vegetative	Aerobes	226.0
		Anaerobes	74.3
		Subtotal	$300.3 \times 63 = 1.9 \times 10^4$
	Spores	Aerobic	301.4
		Anaerobic	0
		Subtotal	$301.4 \times 63 = \dfrac{1.9 \times 10^4}{3.8 \times 10^4 \text{ total}}$
G	Vegetative	Aerobic	231.4
		Anaerobic	104.4
		Subtotal	$335.8 \times 63 = 21.2 \times 10^4$
	Spores	Aerobic	452.0
		Anaerobic	0
		Subtotal	$452. \times 63 = \dfrac{2.9 \times 10^4}{24.1 \times 10^4 \text{ total}}$

The data of Table A-2 reflect a nearly 10:1 ratio in bioload on spacecraft tested under similar conditions and consecutively with the same crew. The actual samples were made at Kennedy Space Center on 26 selected locations all of which were located under the inverted umbrella of the antenna dish. As stated in the reports from John R. Puleo to Dr. Lawrence B. Hall (References 16 and 17), the sampling consisted of cleaning the 2 x 2 inch square areas and testing using NASA Standard Methods. Mr. Puleo, Chief of the HEW Spacecraft Bioassy Unit has cautioned that the two factors, protected sites and cleaned surfaces, must be considered in evaluating these results for future

prognostications of bioload. One further note indicated doubt about the magnitude of the spacecraft surface area.

Other checks have been made by NASA, in particular the data tabulated in the following table, shows a slightly lower level of assayed spore bioload (see Reference 6).

TABLE A-2
Mariner Microbial Load

Spacecraft	Exposed Surface (Vegetatives + Spores)	Total Spore Count
#8	13×10^4	3×10^4
#9 (MM '71)	3.1×10^4	3×10^4

The data obtained do indicate that spacecraft can be built without decontamination (Pioneer) and have spore counts ranging from 10^4 to just over 10^5 microbes, and with decontamination procedures (Mariner) the count can be held to about 10^4 spores. Interest is increasingly directed at spore counts only because of the difficulty in eliminating them by cleaning or wiping procedures. Some spores in fact have D-values running to 20 or more hours at 125°C temperatures.

APPENDIX B
TECHNIQUE FOR SWAB SAMPLING

a. Areas to be swabbed are outlined using sterile cardboard templates
    sterilized in an autoclave at 121°C for 30 minutes. Their sterility is
    ascertained by periodic swabbing of randomly selected templates from their
    sterile container. Each template will delineate a 4 in^2 area.

b. Swabs used for these samplings are made of absorbent cotton on wooden sticks
    which can be readily broken off into sterile diluent with asepsis. Their
    sterility is ascertained by periodically placing randomly selected swabs
    from their sterile container into Brain Heart Infusion (BHI) broth and
    then incubating at 30°C for 72 hours.

c. Diluent for the swab sampling is 0.85% NaCl, sterilized in an autoclave
    while encased in glass in screwcap tubes at 121°C for 30 minutes. Their
    sterility will be ascertained by pour plate as described in f., and g.,
    below.

d. The area delineated by the sterile template is swabbed thoroughly with a
    sterile swab taking care to revolve the swab slowly to prevent dislodging
    already collected microorganisms. When the area is completely swabbed,
    the spent cotton tip is broken off into a sterile glass tube of diluent in
    such manner that the portion of the wooden stick touched by the hand does
    not contact the tube or diluent.

e. The cap is replaced on the diluent tube and the cotton swab material dis-
    persed evenly in the diluent by vortexing for 60 seconds.

f. Serial 10-fold dilutions are prepared from each dispersed swab by removing
    1.0 ml to 9.0 ml portions of sterile diluent in separate tubes. Four such
    dilutions should be made of each swab suspension. These tubes now repre-
    sent 10^0, 10^{-1}, 10^{-2}, 10^{-3}, and 10^{-4} dilutions of the original suspensions.
    The remaining wooden stick is aseptically removed from the 10^0 suspension
    using flame sterilized forceps, and then each dilution is poured into
    respective petri plates marked 10^0, 10^{-1}, 10^{-2}, 10^{-3}, and 10^{-4}. Ninety ml
    of BHI broth containing 1.5% melted agar cooled to 45°C is then added to
    each plate. A blank plate containing no added diluent suspension also
    receives 90 ml of melted BHI agar to ascertain its sterility.

g. All plates are incubated at 30°C for 72 hours, the colonies counted, and reported as 72 hour results.

h. Spore counts are determined by the same procedure except that prior to Step f., the 10^0 suspension is heated to 70°C for 15 minutes to kill the vegetative cells in the sample.

APPENDIX C
A PROCEDURE FOR COMPONENT HANDLING

a. Brown paper bags large enough for components to readily contain the components. They are sterilized in an autoclave at 121°C for 30 minutes. This is done in the container in which the bags are to be stored until used.

b. The container has a readily accessible opening to allow removal of the bags when desired for component storage. Sterility is not mandatory since only maintenance of cleanliness of the probe components is of concern. Thus, no handling procedures beyond those normally practiced in microbiological laminar flow hood are imposed.

c. Each paper bag contains a designated area for clearly marking the name of the component and the date in which it was placed into the paper bag.

d. The component and paper bag are then placed in a plastic bag to prevent dust contamination and placed in storage until it is to be assembled. The plastic bags are a standard clean room type which is never reused once opened.

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APPENDIX D
JOVIAN RADIATION INACTIVATION CAPABILITY

The study of Jovian trapped radiation is included because it significantly reduces externally located microbes. The magnetospheres of Saturn and Uranus are not well defined as yet but it is presumed that they possess one because some decimetric radiation has been detected. Because of its weakness, only occasional bursts of decametric emission have been observed on Earth. Nevertheless, it is prudent to assume that some radiation will be encountered and some effect on external biology anticipated.

The effect of radiation of microbes on probes is categorized as somatic rather than chronic or genetic. Somatic effects produce direct manifestations in the microbes which lead to early inactivation; genetic and chronic effects are associated with animals, such as mice, monkeys, or men, and are long term effects. Data gathered to date indicate that increasing radiation doses produce increasing manifestations. Dose rates and energy levels have variations that prevent simple generalization. High energy protons are not as deadly as low energy protons presumably because they pass through the spore too rapidly. On the other hand electrons at high energies are more effective killers than those at low energies. More dose rate data is required to clarify trends. The analysis of rates can be limited to spores because vegetative microbes are more susceptible to prelaunch removal and will die off more rapidly in the planets.

RADIATION ENVIRONMENT

The Jovian trapped radiation is of a nature and strength that some sterilization of an entry probe will occur. Although the probe mission under study here is primarily targeted to Saturn or Uranus, the goal is a probe that inherently is adaptable to Jupiter or to the satellites of one of the outer planets. Study of the Jovian radiation effects serves as a base for the analysis of the other planets and as an upper bound on all planetary entry probes. The approach consists of defining a model, establishing a baseline entry trajectory (ultimately an optimal corridor), determining the radiant dosages, computing survival fractions of bioloads, and finally establishing

the credit to be taken for maintaining planetary quarantine. The carry over
to Saturn and Uranus is purely inferential since the defined models for these
planets are still speculative. The model of proton and electron fluxes used
in this study is based on the preliminary reduction of Pioneer 10 data returns.
These are subject to revision but are representative of probable steriliza-
tion potential. As seen in Figure D-1, the proton data is scattered and
still somewhat indefinite in the final portions of a descent to the atmosphere.
The dip in the proton curve from 3.4 to 3 R_J is assigned to a sweeping action
of Amalthea (V), which is at a radius of 2.53 R_J, but may be very effective in
removing protons. Verification of this effectiveness awaits additional flybys
such as Pioneer 11. Similarly, the slopes and intercepts at 1 R_J also
require further data before precision in defining the local environment can
be accomplished. This study is therefore qualitative in nature for two
reasons:

o Definition of the environment is arbitrarily defined from 3 R_J to 1 R_J.

o Low energy protons are segregated inadequately from background noise.
The latter problem is particularly troublesome because, as is shown later, the
low energy protons are the more efficient microbe killers.
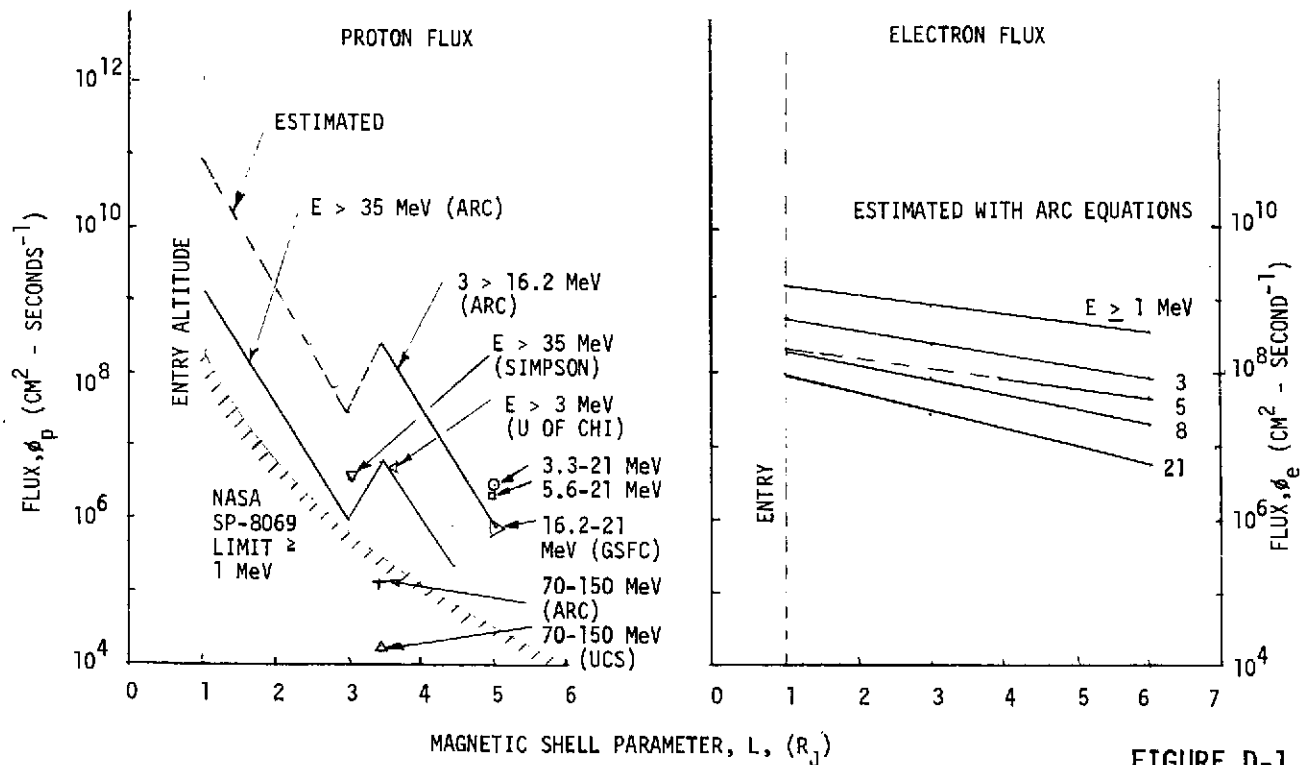
JOVIAN RADIATION ENVIRONMENT

FIGURE D-1

MAGNETIC SHELL PARAMETER, L, (R_J)

The descent history of a probe to atmospheric entry used in this analysis is shown in Figure D-2. It is targeted at a low Jovian entry from the northern hemisphere with an, as yet, minimal attention to wobble of the magnetodisc. An optimal trajectory will be synchronized to penetrate a minimal amount of dense layers of trapped radiation. At least four radiation characteristics need to be considered before final timing of entry is decided:

o Shape of the contours of constant flux (lines of isoflux) to avoid established local concentrations.

o Definition of the dipole location to take advantage of any "South Atlantic" anomaly conditions.

o Sweeping effect of all satellites to minimize encounter with trapped radiation.

o Targeting preferences of terminator proximity (longitude), latitude (zone or band), and relative velocity.

In general, radiant energy encounter is treated as a minus because of damage to electronic equipment directly by electron displacement, etc. and indirectly by macroscopic heating from the energy transferred to all molecules in the probe. The sterilization of bioburden though beneficial to planetary quarantine is heavily counter-balanced by the damage factors. Thus, optimization of early missions is strongly outweighed by the desire to minimize the dose and specific energy levels and rates of exposure. The purpose of this study was to determine whether an appropriate order of magnitude could be established for use in the probability analysis. Actually, no credit was taken for Saturn or Uranus entries even though there remains a possibility of several decades reduction of externally located bioburden on an entry probe.

The procedure followed consisted of numerically integrating the dose using Figures D-2 and D-1. An examination of relative biological effectiveness led to the conclusion that little or no multiplying effect on kill rate can be presumed at this analysis stage; the linear energy transfer (let) function obtained from x-ray and λ-ray doses fails to show a strong effect so the conservative approach consisted of assigning a value of one. These data were drawn from Reference 18.

DESCENT-TO-ENTRY TIME HISTORY

JUPITER ENTRY (4.80°N)

$\gamma = -7.5°$

TIME TO ENTRY
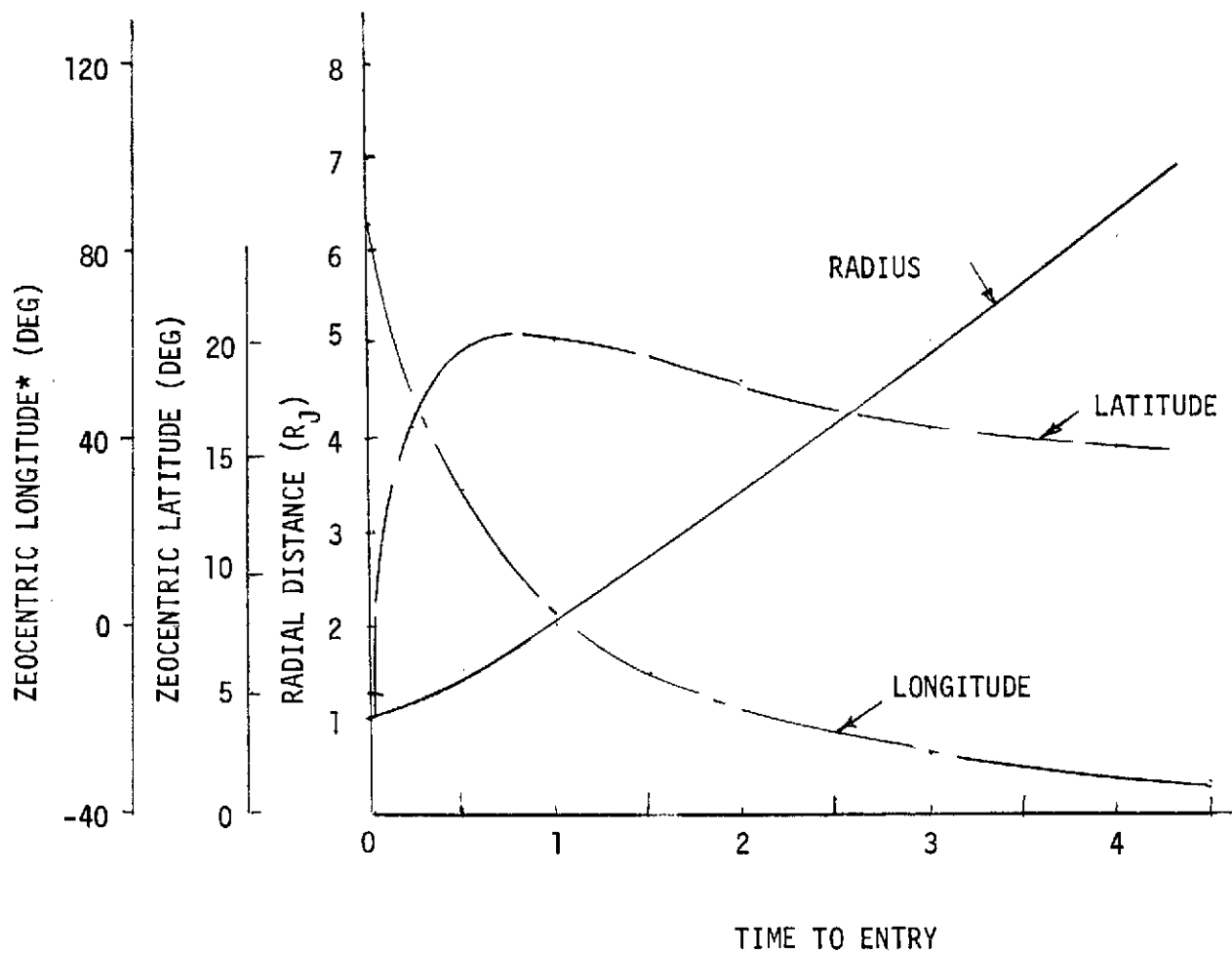
* ZEOCENTRIC LONGITUDE = 0 DEG = SUBEARTH POINT

FIGURE D-2

The radiant energy transmissibility of materials indicates that low energy particles, at least, are only efficient biocidal agents in the multi-layer insulation and on the outer layers of the ablator. Curves for trans-missibility in aluminum (a high nuclear cross-section (Z) metal), carbon and water are illustrated in Figure D-3. Both plastic materials and microbes lie along the water curve so penetration was computed for 5 MeV electrons and protons. Protons at this energy level do not completely penetrate the 30 layers of mylar. The interspersed layers of dacron net were ignored because they have large openings which do not inhibit transmission universally. Electrons at 5 MeV pass through the multiple layers of insulation and the carbon phenolic so they are very effective as a biocidal agent.

TRANSMISSION RANGE OF CHARGED PARTICLES

MYLAR RANGE = H_2O RANGE

5 MeV ELECTRONS = 1.76 CM

5 MeV PROTONS = .025 CM

29 LAYERS @ 6.35×10^{-3} CM = .184 CM
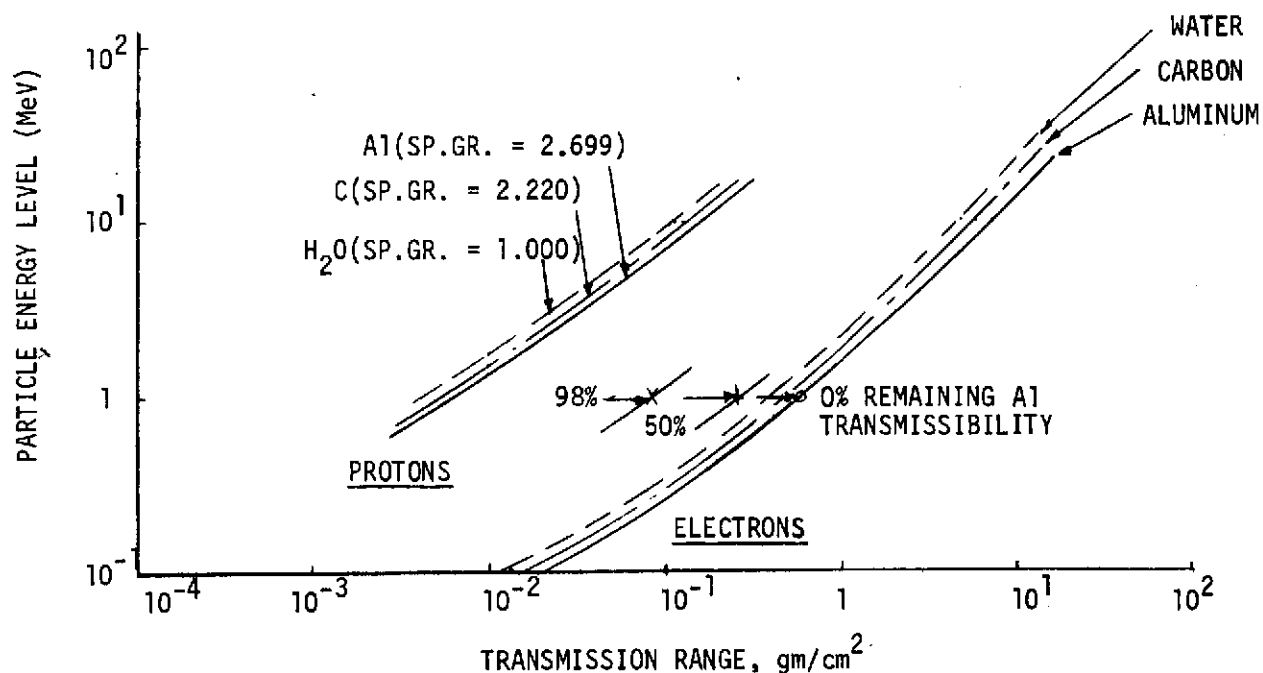
FIGURE D-3

To convert exposure from fluences to dose (in kilorads), Figure D-4 is employed. The fluences of Figure D-5 at known energy levels are multiplied by the dose factor to obtain dose in kilorads. Multiple curves of exposure and survival are eventually needed to get a complete picture of interrelationships.
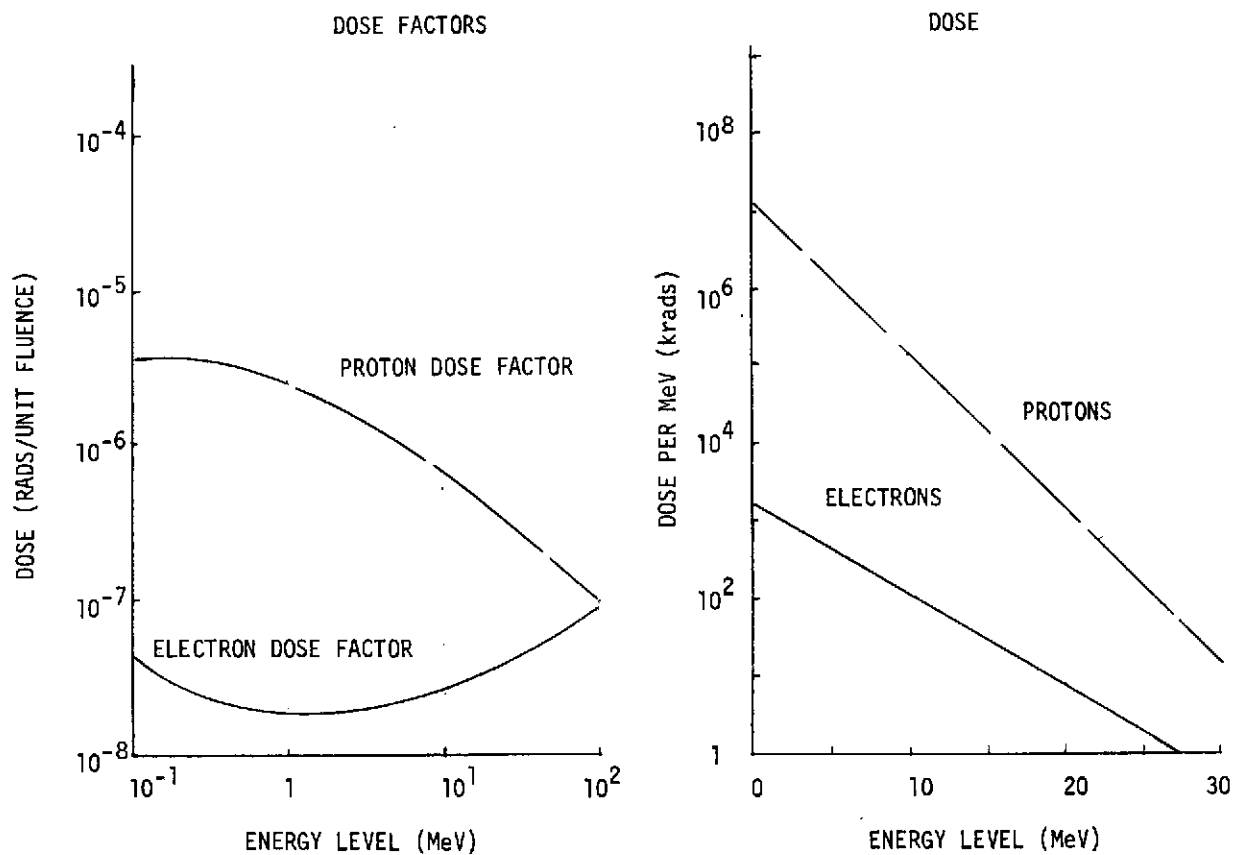
DOSE FACTOR AND ENERGIES

FIGURE D-4

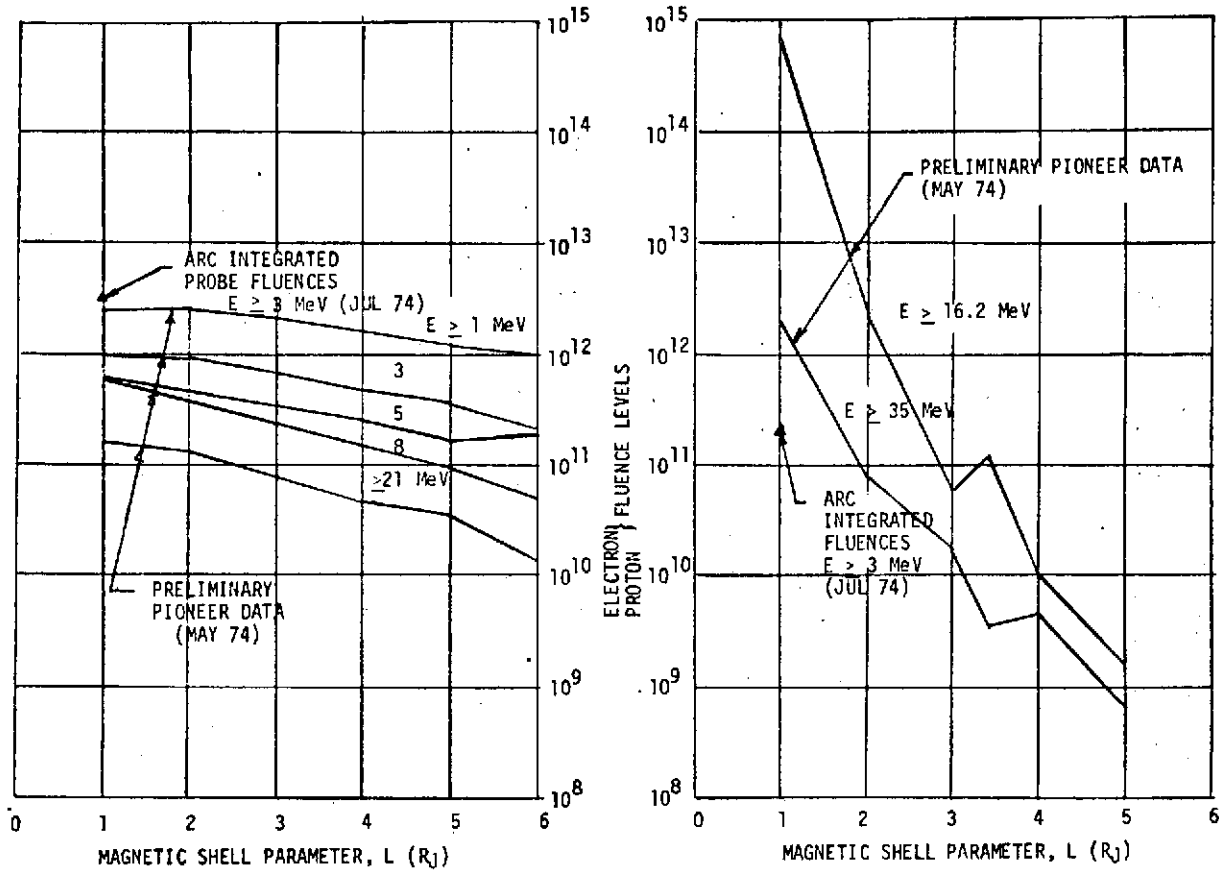# JOVIAN FLUENCE LEVELS

JUPITER - 1979 LAUNCH

FIGURE D-5

Figure D-6 shows the effects of protons at 2 MeV on microbes. The survival fraction of spores is relatively constant over 4 decade variations in dose rate. The survival fraction decreases steadily ($\sim 0.5 \times 10^1$) for a single decade in total dose. From these data it is concluded that kill efficiency increases with total exposure but only one or two decades in the range of 10^3 to 10^4 Krad. The effect on nonspore-formers (vegetatives) is shown for comparison. It can be seen that they are considerably more susceptible when they are present. As stated in the body of report, vegetative microbes are also more susceptible to sterilization techniques prior to launch.

EFFECT OF PROTON DOSE RATE
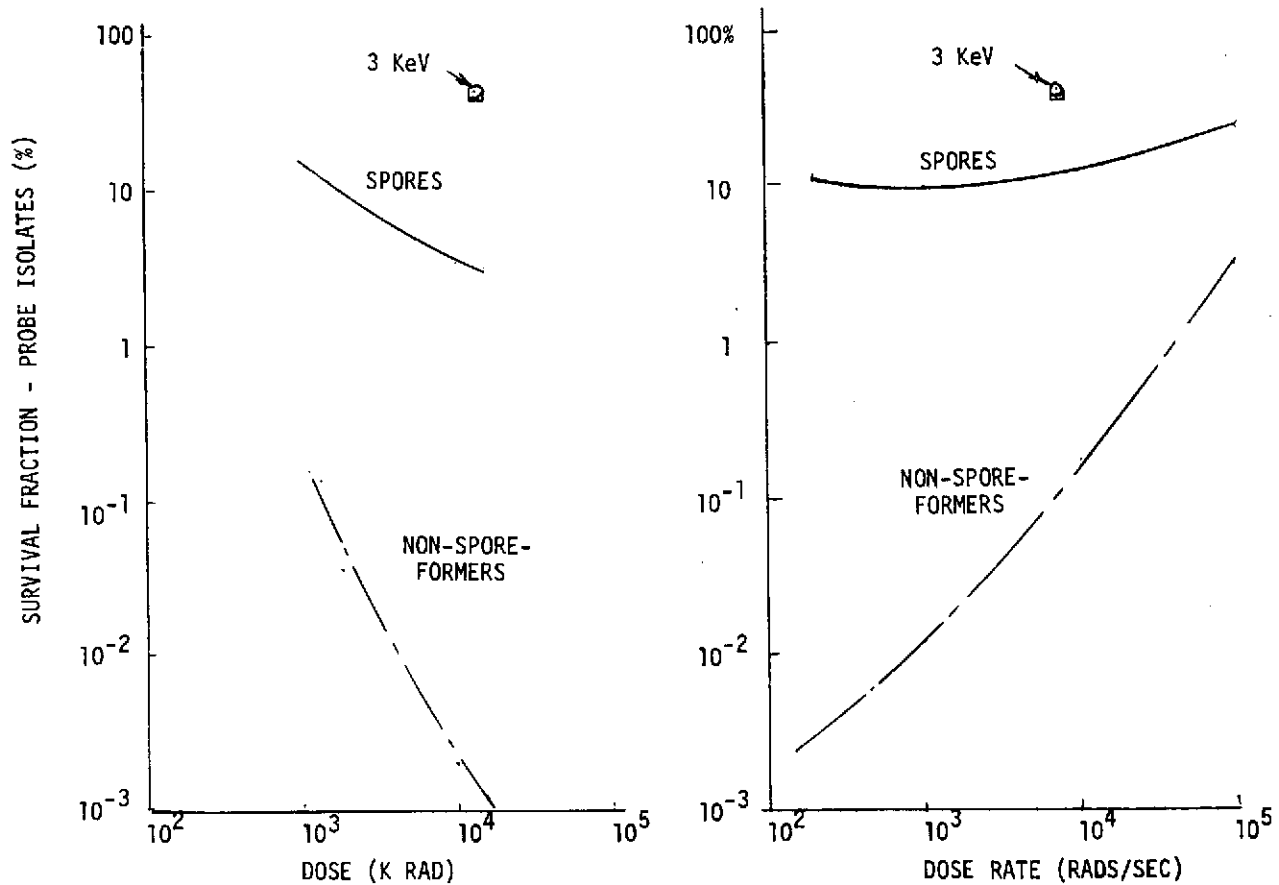
PROTONS AT 2 MeV; DOSE = 2700 K RAD

FIGURE D-6

Electron inactivations are more varied in their effects because data which list dose rates seem to change with energy level but not in a consistent way, as seen in Figure D-7. The kill characteristic is reversed from protons, viz., increasing energy results in decreasing effectiveness. Because of the variability, a conservative value is used in this report. The effects and the nominal value are summarized in Figure D-8. The extrapolations of the data seem to be valid based on the normal behavior of spores in an inactivation environment.

One question in particular is not answered: Are the lethal
characteristics of trapped protons and electrons additive? No convenient
means is available for simultaneous exposure to charged electrons and protons.
The combined heat and γ-irradiation at Sandia Laboratories (References 9 and
10) indicate that combined stresses may produce a synergistic response in
lethality. A simple addition produces upwards of nine decades of microbial
reduction. If synergistic inactivation does occur, this could increase to
10 or 12 decades. In either case an entry in Jupiter's atmosphere is virtually
certain to sterilize the exterior layers of a probe.

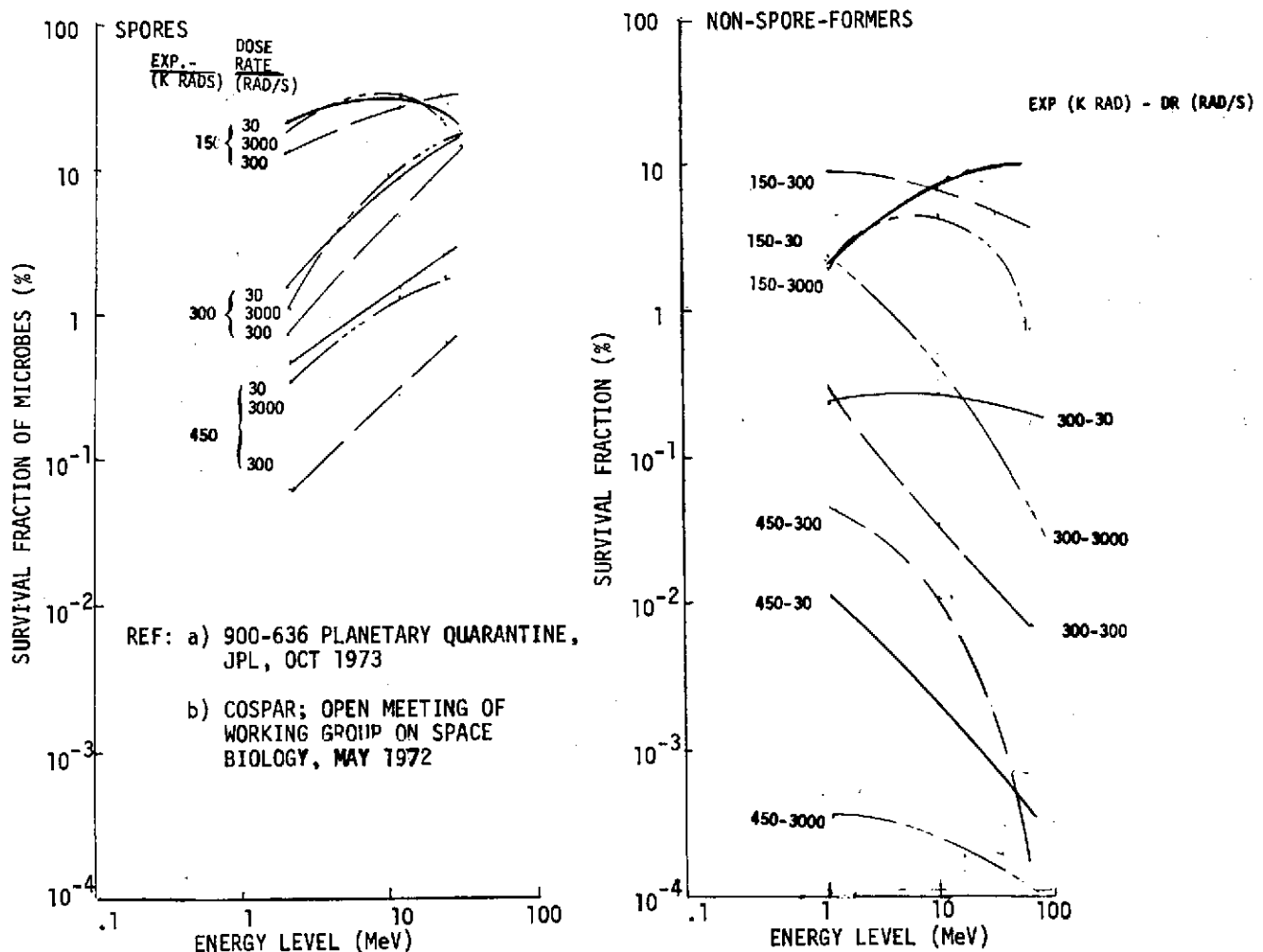## EFFECT OF ELECTRON DOSE ON BIOLOAD

FIGURE D-7

EXTRAPOLATED SPORE SURVIVAL FRACTIONS

o DOSE RATE EFFECTS ARE ASSUMED NEGLIGIBLE
o ADDITIVE OR SYNERGISTIC EFFECTS OF SIMULTANEOUS EXPOSURE TO MULTIPLE
   ENERGY LEVELS AND MULTIPLE KINDS OF IRRADIATION REQUIRES CONSIDERABLE
   TEST VALIDATION
o EFFECT OF LINEAR ENERGY TRANSFER (LET) CONSIDERED TO BE NEGLIGIBLE
o SPORES CONSIDERED TO BE KILLED IF IRRADIATED; THUS, TRANSMISSION DEPTH
   IN MULTI-LAYER INSULATION, ETC. MUST BE DETERMINED
o NON-SPORE-FORMERS SEEM TO BE 10^1 TO 10^3 MORE SUSCEPTIBLE THAN SPORES
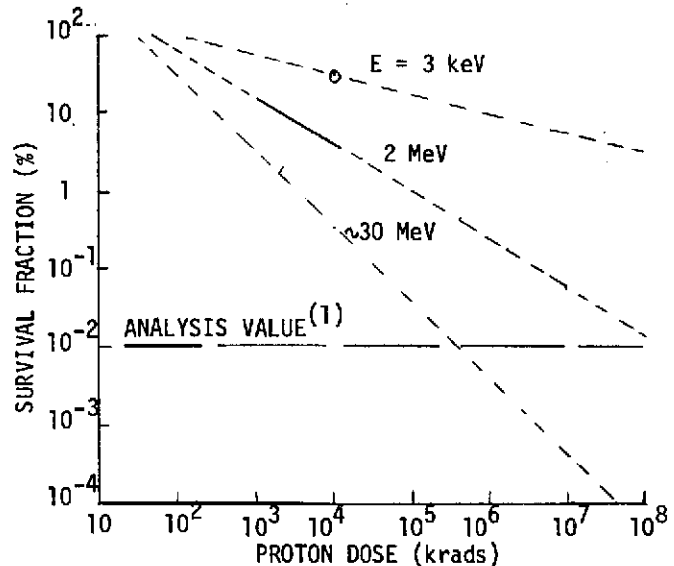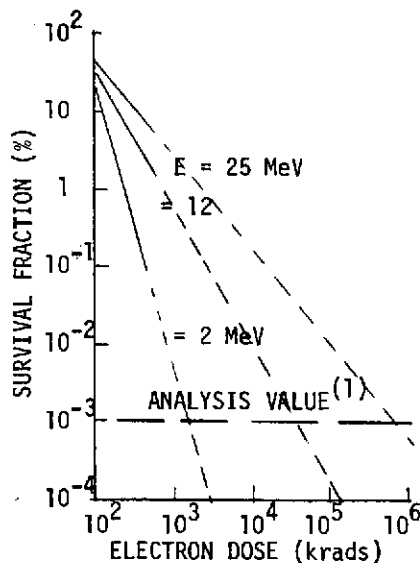
(1) IF IRRADIATION SPORE KILL CAPABILITIES ARE ADDITIVE, THEN 9 LOG
    REDUCTION IS POSSIBLE

FIGURE D-8