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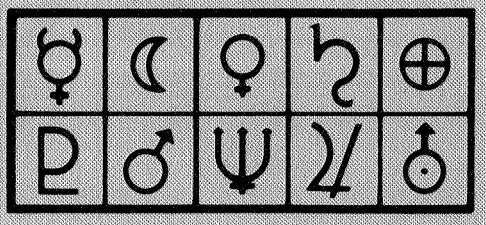

PLANETARY QUARANTINE

THE CHANCES OF RETRIEVAL OF VIABLE MICROORGANISMS DEPOSITED ON THE MOON BY UNMANNED LUNAR PROBES

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ABSTRACT

This study represents an attempt to estimate the density of the bioburden of the moon resulting from unmanned lunar probes.

Accordingly, models are developed which estimate lunar probe bioburdens at launch and upon contact with the lunar surface. For hard impacts, two possible mechanisms for disseminating microorganisms on the lunar surface are modeled: Dispersal in crater ejecta and dispersal on lunar probe fragments. The expected density of terrestrial micoorganisms on the moon is calculated at the time of impact, and subsequent survival is investigated. Some estimates are made of the probability of retrieving a lunar sample containing terrestrial microorganisms deposited by unmanned lunar probes.

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SUMMARY

The objective of this study is the development of a model to (1) estimate the lunar density of terrestrial organisms deposited by automated missions as a function of lunar coordinates and time and (2) estimate the probability that a lunar sample will contain one or more terrestrial organisms deposited by automated missions, again, as a function of location and time.

The study consists of five parts: Initial space-probe bioburdens, bioburden change in cislunar space, dissemination mechanisms at the lunar surface, bioburden changes on the lunar surface, and the probability of sample contamination.

Estimates of initial (at launch) burdens of automated lunar capsules provided by NASA as a result of a sampling program are compared with expected burdens based upon general environmental data. On this comparative basis, all data provided by NASA appears to be conservative in the sense that predicted burdens do not exceed NASA estimates. The NASA estimates are subsequently used.

Based on spacecraft and environmental data, the initial burdens are decomposed into "categories," including: Spore-forming organisms, vegetative organisms, exposed organisms, and occluded and embedded organisms.

The effects of various physical phenomena in cislunar space on each category of organism are assessed. Among the phenomena considered are: Space probe temperatures, vacuum, ultraviolet radiation, ionizing radiation, magnetosphere protection, and "near-earth" radiation belts. The general conclusion reached is that in no case does the burden at lunar impact exceed 30 percent of the burden at launch.

Two possible means of distributing a lunar probe's bioburden about the lunar surface are used: Transport in crater ejecta and transport on space probe fragments. Other types of transport mechanisms are considered and generally discounted as being unimportant or yielding results somewhere between the "extremes" provided by the two mechanisms used.

In examining the transport mode when all microorganisms are attached to parts of the spacecraft, the assumption is that spacecraft breakup is explosive at the known hard-impact velocities. This situation is analyzed to provide both particle velocity and particle range spectrums. By assuming a uniform spatial bioburden on the probe, a lunar bioburden density is obtained.

In the case where it is assumed that all microorganisms are contained in crater debris, calculations are based upon some work of Gault, Shoemaker, and Moore. First, the mass of soil excavated is determined as a function of impact energy. The dispersal of this mass is then analyzed, and the results are graphed as organism density on the lunar surface as a function of distance from impact site. Finally, the long-term time dependence of this burden is analyzed.

For each of the two dispersal mechanisms, the probability of sample contamination per square centimeter of surface taken at varying distances from lunar probe impact sites is discussed.

The conclusions drawn are of a "conservative" nature. These are:

1. Fewer than 30 percent of the microorganisms residing on a typical U. S. lunar probe at launch time survive transit to the moon. The thermal kill of organisms during the typical 34- to 80-hour transit times can be neglected.
2. Seven or eight months after touchdown, the contaminated area around the landing point of a typical U. S. unmanned probe that has made a soft landing should be confined within a conservative radius of 100 meters.
3. Organisms remining on fragments of a typical U. S. lunar probe that has made a hard impact on the moon should be confined almost entirely within a conservative radius of 50 to 60 kilometers about the impact point. These may remain viable for indefinite periods of time.
4. Organisms carried by the crater material formed in the hard impact of a typical U. S. lunar probe may be deposited over the entire surface of the moon. Seven to eight months after impact, however, the contamination of the lunar surface from this dispersal mechanism should be negligible.
5. The distance from the site of hard impact of a typical U. S. lunar probe at which the assumption of uniform deposition of the probe's bioburden over the entire lunar surface becomes a conservative assumption is 240 to 260 kilometers.

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I. INTRODUCTION

By June 1967, 21 unmanned spacecraft launched by the United States and the Soviet Union had reached the vicinity of the moon. Eleven of these spacecraft are known to have terminated their flights by falling into the moon at speeds in excess of the lunar escape speed, while six made soft landings as intended. The remainder were lunar orbiters that apparently fulfilled their missions; some of these orbiters have since fallen into the moon or their orbits have been terminated. Since it is certain that all of these spacecraft were carrying live microorganisms at launch, the possibility that live organisms of terrestrial origin are presently on the moon is a very real one. The purpose of the present study is to explore this possibility in the light of some of its implications for certain scientific objectives of the forthcoming Apollo lunar-landing mission.

To be exact, our concern will center upon the possible effects of the presence of viable organisms of terrestrial origin upon experiments to be performed in the bioscience part of the Lunar Sample Analysis Program [1]. One such experiment will attempt to detect viable organisms that might be indigenous to the moon. Although it is believed generally that the results of this experiment will be negative, it would be tragic if the results were deemed to be indeterminate because of a large chance of the experiment being confounded by the presence of organisms of terrestrial origin deposited by the unmanned lunar probes. It has been suggested that, for a lunar bioassay experiment to be considered successful, the chances of picking up a terrestrial organism should be less than 10^{-6} per square centimeter of the area to be sampled [2]. Obviously, the meeting of such a requirement in a practical situation, where the area to be studied is decided upon by compromise with the needs of the other experiments, is a difficult matter. It is hoped that the results of the present study might make the necessary compromise a more favorable one for the bioassay experiments.

Although the scope of the present report is strictly limited to the transport and survivability of microorganisms upon the moon, it appears that some of our conclusions may also be of interest to those individuals concerned with the organic analysis and biochemistry of the lunar soil samples.

In order to achieve the stated purpose of the study, we shall examine, step-by-step, the means by which earthly microorganisms have been transported to the moon and have been dispersed and deposited there. At each stage of this process, we will attempt to estimate the organism population size and distribution and, in the final stage, to use these estimates in making what are, hopefully, reasonable statements about the chances of retrieving viable terrestrial organisms in any given set of circumstances under which a lunar bioassay experiment might be performed.

II. ESTIMATES OF THE MICROBIAL BURDEN ON LUNAR PROBES JUST PRIOR TO LAUNCH

Sources of the Estimates

Estimates of the number of viable microorganisms residing on or within those unmanned lunar probes reaching the vicinity of the moon prior to July 1967 are shown in Table I, column 3. These estimates have been provided by the Office of Planetary Quarantine, NASA Headquarters, Washington, D. C. [3].

This section will be devoted to an examination of the consistency of the given estimates with the data that is available on the levels of microbial contamination in spacecraft assembly facilities, and to a discussion of the bounds that might be placed on the estimates. An attempt will be made in each case to break down the total burden into the fraction of occluded microorganisms versus the fraction of exposed microorganisms and, for each of these categories, the proportion of spore-formers to vegetative cells.

Beginning with the first of the Surveyor series of spacecraft, the microbial burden on each U. S. unmanned lunar probe has been estimated on the basis of swab sampling data provided by Public Health Service microbiologists at Cape Kennedy, Florida. Selected surfaces on each spacecraft are swabbed with sterile cotton wetted with sterile distilled water. The cotton swab is then transferred to a tube of sterile distilled water and mechanically shaken. Portions of the resulting solution are plated into a growth medium and, after a time of incubation, the number of bacterial colonies appearing on the growth medium are counted. In this way, an estimate of the mean number of viable microorganisms residing on the particular surface is obtained. The results for the selected surfaces are used in an estimate of the size of the viable microbe population on the other surfaces of the spacecraft for which swab sampling is not feasible, and a total burden is then computed by summing the results for all surfaces [3].

TABLE I

Estimates of the Initial Number of Viable Microbes on Unmanned Lunar Probes Reaching the Vicinity of the Moon Prior to July 1967

Spacecraft	Launch Date	Estimated Total Bio-Load (all organisms)	Estimated Total Spore-formers	Estimated Exposed Burden (all organisms)	Estimated Exposed Spore-formers
Luna II (U. S. S. R)	9/12/59	10^8	2×10^7	9×10^7	1.8×10^7
Ranger IV (U. S.)	4/23/62	10^8	2×10^7	9×10^7	1.8×10^7
Ranger VI (U. S.)	1/30/64	10^8	2×10^7	9×10^7	1.8×10^7
Ranger VII (U. S.)	7/28/64	10^8	2×10^7	9×10^7	1.8×10^7
Ranger VIII (U. S.)	2/17/65	10^8	2×10^7	9×10^7	1.8×10^7
Ranger IX (U. S.)	3/21/65	10^8	2×10^7	9×10^7	1.8×10^7
Luna V (U. S. S. R.)	5/9/65	10^8	2×10^7	9×10^7	1.8×10^7
Luna VII (U. S. S. R.)	10/4/65	10^8	2×10^7	9×10^7	1.8×10^7
Luna VIII (U. S. S. R.)	12/3/65	10^8	2×10^7	9×10^7	1.8×10^7
Luna IX (U. S. S. R.)	1/31/66	10^6	2×10^5	9×10^5	1.8×10^5
Luna X (U. S. S. R.)	3/31/66	10^8	2×10^7	9×10^7	1.8×10^7
Surveyor I (U. S.)	5/30/66	5×10^5	5×10^4	4.5×10^5	4.5×10^4
Lunar Orbiter I (U. S.)	8/10/66	5×10^4	5×10^3	4.95×10^4	4.95×10^3
Luna XI (U. S. S. R.)	8/24/66	10^8	2×10^7	9×10^7	1.8×10^7
Surveyor II (U. S.)	9/20/66	2×10^6	5×10^4	4.5×10^4	1.1×10^3
Luna XII (U. S. S. R.)	10/22/66	10^8	2×10^7	9×10^7	1.8×10^7
Lunar Orbiter II (U. S.)	11/6/66	7×10^6	7×10^5	6.93×10^6	6.93×10^5
Luna XIII (U. S. S. R.)	12/21/66	10^7	2×10^6	9×10^6	1.8×10^6
Lunar Orbiter III (U. S.)	2/4/67	2×10^6	2×10^5	1.98×10^6	1.98×10^5
Surveyor III (U. S.)	4/17/67	5×10^6	5×10^4	4.5×10^4	4.5×10^2
Lunar Orbiter IV (U. S.)	5/4/67	2×10^6	2×10^5	1.98×10^6	1.98×10^5

Data from the direct bioassay of the Ranger series of lunar probes is not available. The estimates of the microbial burden for the Rangers are conservative and are probably intended to fall between two extreme values that have been proposed. The early experience with the Ranger lunar probes indicated that one should expect about 10^9 viable organisms on the craft prior to sterilization [4]. As a result of later work, this number was revised downward to about 10^7 organisms before sterilization, and although every Ranger has been subjected to some decontamination measures, the given estimate of about 10^8 viable organisms stands as a conservative but reasonable compromise.

The figures given in Table I for the burdens on all but two of the Soviet Luna spacecraft are at best intelligent guesses based on the assumption that the microbial environment, assembly procedures, and methods of decontamination in spacecraft assembly facilities in the Soviet Union are not radically different from those in the United States. The burdens given for Luna IX and Luna XIII are less than the estimates for the others of their series, and this reflects the fact that a more explicit account was given by Soviet sources of the sterilization procedures applied to these spacecraft prior to launch [3].

Consistency of the Estimates

There are three major sources of microbial contamination on spacecraft: (1) Microorganisms may become imbedded or encapsulated in certain piece parts of the spacecraft while the parts are being fabricated; (2) airborne microorganisms present in the spacecraft assembly area may come in contact with and adhere to exposed surfaces on the spacecraft during assembly; and (3) microorganisms are transferred from human beings to the spacecraft by direct contact with fingers, clothing, and tools.

Electronic components, potting and insulating materials, and solid rocket fuels have the highest potential for containing imbedded or encapsulated microorganisms since they are all generally fabricated at temperatures that are tolerable to spore-forming cells. Some data relevant to the internal microbial burden of electronic components has been published by Phillips and Hoffman [5]. An interpretation of this data that is applicable to the present study has been made by Davies and Horowitz [6] who have also had access to the unpublished results of similar work by D. Portner. The conclusion of Davies and Horowitz (with 99 percent confidence) regarding this material is that less than 4 percent of all the electronic components sampled were detectably contaminated. According with their interpretation, one might expect that the 35,000 to 60,000 electronic piece parts of a United States lunar probe [7]

would contain fewer than 1400 to 2400 detectable infective centers. Although the average number of microorganisms per infective center is unknown, it is probably safe to assert that the internal burden contributed by the electronics parts in a lunar probe is less than 10^4 viable organisms. The interiors of other, solid materials such as metals and optical glass have a high probability of being sterile.

The problem of microbial contamination of exposed spacecraft surfaces by fallout of airborne microorganisms has received considerably more attention than the problem of interior contamination. The measurement of the rate of deposition of airborne microorganisms is currently being accomplished by exposing a number of sterile stainless steel strips in the environment (clean room, assembly area, or factory area) under study and then assaying the surfaces of one or more of the strips for the microbial density at different times after the beginning of the exposure. The pertinent results of several recent surface sampling studies are summarized in Table II. The surface densities of microorganisms in these results are said to be "stabilized" because the plot of density versus time of exposure generally shows a plateau, or steady state, after an exposure of 18 to 25 weeks. (See also the discussion in Appendix A concerning the "plateau effects.") It is clear that the surface density of microorganisms observed in different geographic areas, or in environments subject to different degrees of contamination control may vary by a factor of at least 100. Seasonal and short term variations (mainly caused by human activity in the assembly areas) are also observed [8].

McDade, Favero, et al. [8] have found that the stainless steel strip method of measuring surface deposition of microorganisms gives results that compare favorably with the results of measurements taken on horizontal surfaces of the spacecraft itself. They also find no significant differences when glass and lucite strips are used in place of the stainless steel strips, although there is some evidence that electrostatic forces should increase the surface density on surfaces made of plastics by factors of 3 to 5 [9].

Thus, on the basis of the surface sampling studies just summarized, one would expect that the number of viable microorganisms residing on a typical U. S. lunar probe (with surface areas between 400 and 600 square feet) prior to the application of any decontamination measures would lie between 10^4 and 10^8. Taking the nominal value rather than the extreme values, namely a 500 square foot area and a stabilized density of 5×10^3 organisms per square foot, one finds a surface burden of 2.5×10^6 organisms before decontamination. These rough estimates, of course, do not yet include the contribution made to the surface population of viable microbes by direct contact of portions of the spacecraft with personnel or tools.

TABLE II

Results of Some Surface Sampling Studies of Fallout of Airborne Microorganisms

Geographical Area (U.S.)	Type of Facility	Observed Stabilized Density of Viable Aerobic Mesophiles (No./ft)	Time to Stabilize (weeks)	Source
West Coast	JPL spacecraft assembly area	$5 (\pm 4) \times 10^3$	25	[8]
	Conventional clean room (Class III)	$10 (\pm 2) \times 10^3$	24	
	Conventional clean room (Class II & IV)	$\sim 5 \times 10^2$	24	
Pheonix, Arizona	Manufacturing area	$5 (\pm 2) \times 10^4$	18	[8]
	Conventional clean room	5×10^3 to 10^4	18	
East Coast	Assembly area	2×10^2	?	[6]
	Conventional clean room	8×10^2	?	
	Factory area	6×10^3	?	

The contamination of spacecraft parts with microbes by human handling is more difficult to predict in a quantitative manner. There appears to be much variation from person to person in the number of microorganisms that each deposits during a contact, and, furthermore, there does not seem to be much published information regarding the frequency and extent of contact of spacecraft parts and surfaces with human fingers. Most of the data that is available is based upon controlled studies of personnel handling sterile stainless steel strips (see, for instance, Reference 8). This data indicates that as many as 200 microorganisms may be deposited by handling on a 1- by 2-inch stainless steel strip, although the average number so deposited is more like 16 per strip. The use of finger cots or gloves may reduce the deposition by one order of magnitude or more. Also, there is some evidence that the number of organisms transferred to a strip by an individual at each touch generally decreases with each subsequent touch by the same individual during the handling sequence [8].

On the basis of these observations, one is very likely being conservative if he sets the contribution made by human handling to the surface burden of a spacecraft at 100 organisms per square inch of surface. For a 500 square foot area, such a density implies a total contribution of 7.2×10^6 organisms.

Thus, the picture which emerges from the brief survey just made suggests that a lunar probe of the type being considered, assembled in a facility with only a moderate environmental contamination control, would be expected to have a total burden of 10^6 to 10^7 viable microorganisms at completion of the assembly if no efforts were made to clean or disinfect its surfaces and piece parts. When the currently accepted decontamination procedures for U.S. unmanned lunar probes [3] are applied during assembly, 60 to 98 percent of the population of microorganisms residing on the surface may be removed, according to the experience of at least one source [10]. The post-decontamination total burden would then amount to 10^4 to 10^6 viable microorganisms. Such a range of values is consistent with estimates of the total burden at launch for the Surveyor and Lunar Orbiter probes (Table I). The only clear bounds that may be placed on the estimates shown in Table I are those suggested by the extremes in the data on levels of contamination contributed by the three sources discussed previously. Such data that is currently available indicates that the given estimates for the Surveyor and Lunar Orbiter series of space probes cannot be in error by more than an order of magnitude, and that the estimates for the Ranger series and, possibly, the Soviet spacecraft should be considered as upper limits of their total microbial burdens.

In particular, it should be obvious that the means by which the microbial burdens on the spacecraft were estimated make it impossible at the present time to place statistical bounds (confidence limits) upon the estimates. The labor involved in gathering a sufficient amount of data by the swab sampling technique so that nonparametric methods in statistics may be used to analyze the data is probably prohibitive. If one still wishes to make a statistical analysis with limited data, the alternative to nonparametric methods is the construction of a stochastic model of the deposition and removal of microorganisms on the spacecraft surfaces during assembly and then use of the data to estimate the magnitude of the parameters of the model. To the author's knowledge, this latter approach has only recently been tried [11] and the resulting model has never been implemented. A model more limited in applicability and intended only to describe the surface burden resulting from the fallout of airborne microorganisms is described in Appendix A of this report. One result of this model seems to suggest that that portion of the microbial population on the spacecraft resulting from the fallout of organisms in the intramural environment of an assembly facility should, under certain circumstances, be Poisson distributed; this, for large populations, is the same as being normally distributed with a given mean and a variance equal to the mean [12]. If this result could be experimentally verified, then confidence limits for at least the fallout contribution could be derived on the basis of the more limited data resulting from current spacecraft microbial assay procedures. However, the use of a Poisson distribution to obtain confidence limits on the estimated burdens shown in Table I would not be justifiable because of the way in which these estimates were obtained. A stronger objection to the use of the Poisson distribution is the apparent lack of experiments that might indicate the correct model to use in organizing the data that is available for the several lunar probes listed in Table I. Thus, insofar as can be determined practically, the bioburden estimates given in Table I appear to be consistent with estimates that may be derived from various environmental studies.

Qualitative Aspects of the Microbial Burden and Estimates of the Exposed Burden on the Lunar Probes

From the standpoint of planetary and lunar contamination, perhaps the most important distinction to be made among the microorganisms residing upon a spacecraft is that between spore-forming and vegetative cells. Certain bacteria may grow and reproduce for many generations as vegetative cells. However, at some stage in the development of the culture and depending upon the environment, sporulation may commence and the vegetative cells

will transform themselves into small, highly resistant cells known as spores. All organisms in the genera Bacillus and Clostridium may produce spores under certain conditions. In general, the spore is much more resistant to heat, ultraviolet radiation, and ionizing radiation than its counterpart in the vegetative state. It is therefore of obvious importance to be able to estimate the fraction of the microbial burden on a spacecraft that are spores or spore-formers.

Since aerobic spore-formers are generally associated with soils, it is to be expected that the less rigid the environmental control in an assembly area, the larger should be the concentration of spore-formers in the intramural air. The results of McDade, Favero, et al. [8] seem to confirm this expectation. They found that the predominant types of microorganisms that accumulated on stainless steel strips exposed in the two manufacturing areas studies were Bacillus spore-formers and molds. The percentages were 39.9 and 21.5 percent, respectively. The concentration of spore-formers in one class 100,000 clean room was also high--about 55 percent. Results of studies of more rigidly controlled clean rooms showed a marked absence of microorganisms associated with soils and a predominance of organisms associated with the skin and respiratory tract of humans. These later organisms, predominately Staphylococcus and Micrococcus in one study, do not survive storage for very long in places where there is no possibility of replenishment by fallout of airborne bacteria. For instance, the total population of aerobic microorganisms of a surface at ambient temperatures and humidity, after being covered with sterile aluminum foil, decreased by 50 percent in 2 weeks and then remained at a constant level. It was found that the majority of the survivors were mainly spore-formers, molds, and actinomycetes.

It should also be noted that in the environmental study just reviewed, molds contributed 23 to 25 percent of the types of aerobic mesophilic organisms which were found to accumulate on stainless steel surfaces exposed to the intramural air of the two manufacturing areas.

Fortunately, direct estimates have been provided for the percentage of spore-formers to be found on the Surveyor and Lunar Orbiter series of spacecraft [13]. After cleaning and decontamination, the swab sampling data from all Surveyors (II through VI) showed that the average number of spore-forming bacteria remaining on the surface was about 0.5 percent of the total surface burden. Similar data for the Lunar Orbiters (III through VII) showed 8 percent of the burden being spore-formers. These numbers should give the average number of spore-formers on the spacecraft surfaces at launch since the craft were encapsulated and protected from particles greater than 0.3 micron size from the time of the sample survey until the time of launch. However, in Table I, column 4, the estimated total number of spore-formers on all but one of the Surveyors and on all the Lunar Orbiters are given as

1 percent and 10 percent, respectively, to be slightly conservative. Surveyor I is the exception in that the direct estimates provided by Mr. Puleo [13] do not include any sampling data from that craft. The estimated number of spore-formers on Surveyor I has been set at 10 percent of the total burden.

In estimating the number of spore-formers residing in or upon the other unmanned lunar probes listed in Table I at the time of launch, one must necessarily use the information provided by the previously mentioned study of McDade, Favero, et al. [8], since direct sampling data on the Ranger and Luna series is lacking. The percentages of spore-formers accumulating in the manufacturing areas are likely to be conservative. On the other hand, it has been shown that the absolute burdens on these craft are conservative. Therefore, an estimate of 20 percent spore-formers (representing roughly the lowest value observed for an uncontrolled manufacturing area) has been adopted for the Ranger and Luna series in column 4 of Table I.

Next, the estimated exposed burden on the several lunar probes will be examined. For the purpose of the present study, the word "exposed" shall mean: accessible to solar ultraviolet radiation. In practice, the definition of exposure is the same as the usual one, i. e., location on a surface that is normally uncovered in flight. From the discussion of the sources of spacecraft microbial contamination given in previous paragraphs, it is seen that all but a small percentage of the viable microbes are likely to reside on surfaces, the internal encapsulated burden being relatively small. However, during assembly, some of the surfaces are covered by the mating of components, the sealing-off of compartments, and other such operations. For the Surveyors, the surface area occluded in such a way amounts to about 30 square feet, or less than 10 percent of the total surface area. For the Lunar Orbiters, the occluded surface area is about 2 square feet or 0. 5 percent of total surface area [13]. Clearly, for the aims of the lunar contamination survey, the occluded microbial burden corresponding to such small areas is unimportant and is well within the uncertainties in the estimates of the total burden. Nevertheless, a figure of 90 percent of total burden has been assigned to the exposed burden in column 5 for the Surveyors listed in Table I, and a figure of 99 percent of total burden has been correspondingly assigned to the exposed burden in column 5 of the Lunar Orbiters in Table I. Since spore-formers have such long natural lifetimes, even under adverse conditions, it presumed that the fraction of the total burden that consists of spore-formers is preserved in the distinction between occluded and exposed populations. The resulting values are shown in column 6 of Table I.

It will be seen in the sequel that the exposed burden on a spacecraft has the largest chance of being scattered to great distances upon impact. (On the other hand, it is clear

that exposed microorganisms are the most vulnerable to the ultraviolet and ionizing radiations of space.) Thus, it is difficult to assign conservative values to the Rangers and the spacecraft of the Luna series in the absence of any direct measurements or more detailed knowledge of their geometry. The reasoning behind the estimates shown in columns 5 and 6 of Table I for these two series of spacecraft is the following: A 20 percent occluded surface area is an upper limit on the basis of photographs and drawings of the Rangers and of most of the Lunas. Since the estimates of the total burdens on these craft are likely to be conservative, a 10-percent-of-total-burden figure for the occluded burden is not likely to underestimate the occluded population. Therefore, the 10 percent factor is used. Again, it is assumed that the relative number of spore-formers is preserved in the distinction between exposed and occluded populations.

storms. The peak electron flux is about 2 x 10^8/cm^2-sec [19]. The unshielded maximum dose rate would then be about 10^5 R/hr [18]. A belt of trapped low-energy protons coinciding roughly with the outer electron belt has also been observed. These protons have a peak flux of 2 x 10^8/cm^2-sec and energies between 0.1 MeV and 5 MeV [19]. The maximum unshielded dose rate could thus be as high as 10^6 R/hr in the outer belt, solely on the basis of these low-energy protons [18].

The existence of the solar wind, first predicted by Eugene Parker, has been demonstrated with measurements made on several spacecraft (Luniks I and II, Explorer X, Mariner II, Mars I, and IMP-I). These experiments show that there is a continual flux of positive ions from the sun that consists mostly of hydrogen. At the earth's orbit but outside of the magnetosphere, the direction of flow is within a few degrees of the sun. The ion flux observed by IMP-I was about 3 x 10^8/cm^2-sec with energies per particle in the 300 to 1000 eV range [20]. The IMP-I satellite was also able to roughly map the boundaries of the magnetosphere on its sunward side. Apparently, the sunward boundary of the magnetosphere lies at about 10 to 13 earth radii (~63, 500 to 82, 550 km). In the antisolar direction, the magnetosphere resembles a tube with axis roughly parallel to the earth-sun line and a diameter of roughly 40 earth radii [19]. This "tail" region of the magnetosphere probably extends at least as far as the orbit of the moon. The moon, if it does pass through the magnetosphere, should spend about 9 days within it. The solar wind protons that have diffused into the magnetosphere are probably Maxwellian-distributed with a kinetic temperature of approximately 100 eV and a particle flux of about 10^4/cm^2-sec [21].

The surface dose rate for the solar wind outside of the magnetosphere is about 10^6 R/hr with negligible internal dose [18].

The primary cosmic radiation present in the inner solar system consists of protons (85 percent), alpha particles (13 to 14 percent), and a small number of nucleii with $Z \geq 3$. The particle flux is isotropic and varies with the 11-year solar cycle from 2/cm^2-sec to about 4/cm^2-sec. The energies of these particles range from about 20 MeV/nucleon to as high as 10^{12} MeV/nucleon, although particles of these high energies are rare. Volynkin, et al. [22] have estimated a surface dose rate of about 10^{-3} R/hr for the primary cosmic radiation. Cosmic ray secondaries (the result of interaction of the primary cosmic radiation with matter) may produce a dose rate within a spacecraft of 10^{-3} R/hr or higher, depending upon the amount of matter traversed [18].

The solar cosmic rays originate in solar flares in the sun's chromosphere. An hour or so after the occurrence of a solar flare, an isotropic flux of energetic particles, mainly protons, fills space in the vicinity of the earth. After reaching a peak value, the intensity

decreases with a characteristic decay time that depends upon the particular energy group of the particles. The decay time may vary from 2 to 4 hours for high-energy particles to several days for the very low energy particles. Unshielded dose rates from solar flare protons of the highest energies (12 to 20 BeV) may be as high as 10^4 R/hr [23]. However, the solar flares with which the most energetic protons are associated occur roughly every 4 or 5 years and during the period of declining solar activity. The last recorded high energy flare occurred on February 23, 1956. Medium energy flares, characterized by protons having energies of a few BeV, occur roughly two to four times a year during years of high solar activity. The last recorded medium energy flare occurred on November 12, 1960. Low energy flares (proton energies of the order of 100 MeV) generally occur 10 to 12 times a year, but few have been observed since 1959; therefore, it is not likely that solar flare particles have had any significant effect upon living organisms residing on lunar probes launched since 1960.

The Viability of Microorganisms in Cislunar Space

According to the summary of physical conditions in space, it would appear that even in the absence of ionizing radiations, any microorganism residing on an exposed surface of a lunar probe vehicle would at least be subjected to a vacuum of 10^{-10} torr or less, and would be in contact with a dry surface at a temperature of 60°C or less. In addition to this, those microorganisms exposed on the sunlit side of the vehicle would be illuminated with solar ultraviolet radiation lying in a particularly lethal band of wavelengths.

The combined effects of ultrahigh vacuum and temperature on the viability of spores and vegetative cells have, fortunately, received some experimental investigation. Portner, Spiner, Hoffman, and Phillips [24] exposed two species of spore-formers, Bacillus subtilis var. niger and Aspergillus fumigatus, and vegetative cells of Mycobacterium smegmatis, to vacuums of the order of 10^{-10} mm Hg and temperatures of 23° to 24°C for a period of 5 days. Their results showed essentially no difference in the viability of the exposed organisms and the control population after this time.

Davis, Silverman, and Keller [25] studied the survival of the spores of five organisms in vacuums of the order of 10^{-8} to 10^{-10} torr and over a temperature range of -190° to 120°C. They found no significant decrease in the recoveries of these five organisms when they were subjected to the vacuum and temperatures less than 25°C for 4 to 5 days. However, after 4 to 5 days exposure at 53°C or 60°C in ultrahigh vacuum, less than 14 percent of the spores of Bacillus stearothermophilus survived, and less than 2.6 percent of the

spores of Bacillus megaterium survived. In the same series of experiments, some idea was obtained of the survivability of soil organisms in ultrahigh vacuums and at temperatures between 40°C and 120°C. However, the exposures of the organisms were made without separation from the soil, and no indication of the degree of protection offered by the soil to the organisms could be given.

The effect of ultrahigh vacuum on vegetative cells has also be studied by Silverman and Beecher [26]. They found that, at temperatures between 4°C and 40°C and pressures of 10^{-10} torr, a 5-day exposure of the organisms Staphylococcus aureus and Streptococcus faecalis resulted in a decrease in the level of viability that depended upon the organism. Under the stated conditions, the percentage survival of S. aureus stabilized at 4 to 8 percent and the fraction for S. faecalis stabilized at about 10 percent. A sharp decrease in the viability of the organisms was exhibited for temperatures above 40°C. At 60°C, for instance, the survival fractions for both organisms were about 10^{-3}.

The results of similar experiments by Imshenetsky and Lysenko [27] seem to support the evidence described in the preceding paragraphs. Under the action of high vacuum at 10^{-8} to 10^{-9} mm Hg and at -23°C for 72 hours, all seven species of spore-forming bacilli examined remained viable. For asporogenic bacteria subjected to the same conditions, the survival fraction was essentially zero for Pseudomonas pyocyanea, Escherichia coli, Pseudomonas fluorescens, Serratia marcescens, and Vibrio metchnikovii. Sarcina flava and Mycobacterium rubrum showed about 30 percent survival. The mycelia of fungi proved to be quite resistant under these conditions.

Some idea of the resistivity of microbial spores to ultraviolet radiation after exposure to ultrahigh vacuum can be gained by examining the work of Silverman, Davis, and Beecher [28]. In this study, spores were first subjected to vacuums in the 10^{-9} to 10^{-10} torr range for 5 to 7 days and then exposed to ultraviolet or gamma radiation either while still under vacuum or in the presence of dried air. The exposure in either condition was at ambient (~20°C) temperatures. The source of ultraviolet radiation was a General Electric Type G15Ta mercury germicidal lamp, while irradiation by gamma rays was accomplished by submersion in a Cobalt-60 irradiation unit. The presently relevant part of their results for ultraviolet effects show percentage of survivors defined by

$$f = \frac{\text{no. of spores vacuum dried and irradiated in vacuum}}{\text{no. of spores exposed to vacuum but shielded from UV light}} \times 100,$$

as a function of the radiation dose in μwatt-sec/cm^2. A dose of 750 μwatt-sec/cm^2 was sufficient to give f's less than 1 percent for spores of B. megaterium, B. subtilis var.

niger, and B. stearothermophilus. Spores of Aspergillus niger were the most resistant, 83 percent surviving a dose of 1000 μwatt-sec/cm^2.

For vacuum-dried spores subjected to gamma radiation in vacuum, it was found that 4×10^5 rad was required to cause 99 percent destruction of spores of B. megaterium, and about 3.2×10^5 rad for 99 percent destruction of Clostridium sporogenes. On the other hand, spores of Aspergillus niger were the most sensitive to gamma radiation; about 10^4 rad was required for 99 percent destruction of these spores.

The ultraviolet dose at 2537 Å that is necessary to inhibit growth in vegetative cells seems to be always about one-half that required for inhibition of cells in the sporulative state [28, 29], although the lethal dose is highly organism-dependent and may also vary with the humidity, pressure, and temperature [29]. For both spores and vegetative cells, the decrease in viable population under irradiation by ultraviolet light appears to follow an exponential law (see Appendix B).

It now remains to try to assess the effects of the ionizing radiations present in cis-lunar space on the viability of microorganisms. It is clear that the major effects, if any, should be caused by the proton and electron components of the various space radiation fluxes mentioned earlier, since these particles are the most abundant and energetic. Unfortunately, the law of population decrease in the presence of ionizing radiation does not take the simple form that it does for ultraviolet radiation. The curves giving the logarithm of the number of survivors as a function of dosage show strong nonlinearities in many cases [28]. But what is even more vexing is that the mean lethal dose--when such a quantity can be defined--is highly dependent on the type and energy of the ionizing radiation, and there does not seem to be any sound way of deducing the mean lethal dose for, say, irradiation by 100 MeV protons from, say, Silverman's data on survival under irradiation by gamma rays. The problems associated with the prediction of effects of ionizing radiations on the viability of microorganisms and the relative effectiveness of the different types of radiation are explored in more detail in Appendix B.

The conclusions of other individuals concerned with the effects of ionizing radiations, and in particular the cosmic radiation, on microbe viability tend toward the view that ionizing radiation is unimportant as a sterilizing agent. Some early work of Sagan [30] (which is treated in detail in Appendix B) suggests that cosmic radiation would have to illuminate only slightly shielded organisms for 10^8 years before substantial kill would result. Without stating their reasons, Geiger, Jaffe, and Mamikunian [2] conclude that cosmic rays and solar flare protons would be insufficient to effect any substantial sterilization of a spacecraft in transit to one of earth's neighboring planets. Such a conclusion is certainly

supported by Sagan's calculation if the possibility of even very small amounts of shielding overlaying the microorganisms on the spacecraft is admitted.

Application to the Unmanned Lunar Probes

Some conclusions may now be drawn regarding the amount of microbe die-away that occurred on the several lunar probes between launch time and impact on the moon.

First, it seems very likely that thermal kill of the spore-forming microorganisms can be disregarded. According to the results of some of the experiments that have been summarized, the exposure of spores to high vacuums and temperatures below about 40°C is not lethal for periods of at least 4 to 5 days. If the temperature distributions for the Surveyor spacecraft are typical of all the lunar probes, then it appears that temperatures in excess of 40°C occur mainly on the sunlit side of the craft where—for exposed organisms—the solar ultraviolet radiation proves to be the more lethal agent. The number of spore-forming bacteria located on surfaces that are shielded from solar radiation, yet are still exposed to temperatures in excess of 40°C and to the high vacuum of space, should be small in relation to the size of the exposed population.

For thermal kill of vegetative cells in high vacuums, the results of Silverman and Beecher [26] suggest that a D-value of 120 hours be adopted for those organisms which are exposed to temperatures below 40°C. For temperatures near 60°C, their data indicates a D-value of about 40 hours, but again, the thermal kill occurring for exposed vegetative cells on the higher temperature surfaces of the spacecraft is probably dominated by the lethal effects of ultraviolet radiation or solar wind protons.

The ultraviolet radiation dose in a high vacuum required to reduce an exposed spore population to one-tenth of its original size is between 3750 ergs/cm^2 and 1.24×10^5 ergs/cm^2, by way of rough estimates based on the results of Silverman, Davis, and Beecher [28]. The higher value applies to resistant spores such as Aspergillus niger, which are probably rarely found on U. S. spacecraft. Nevertheless, the energy flux of the full solar ultraviolet radiation in a narrow band of wavelengths about 2537 Å is about 200 ergs/cm^2-sec and so, even for these higher R_{10} values, the exposure time in direct sunlight required to reduce the spore population by one decade is only 6200 seconds, or less than 2 hours. Since these estimates are conservative, one may immediately conclude that unshielded spore populations directly irradiated by the sun are reduced to a negligible size during a flight of 30 hours or more. The conclusion is even more valid for exposed populations of vegetative cells since the R_{10} values applying to them are smaller.

The considerations in Appendix B suggest that solar wind protons may degrade the size of the microbial population by a factor of 0.1 every 31 to 2700 seconds of exposure. What is presently known about the structures of the solar wind and the earth's magnetosphere give some evidence that such a high rate of kill would apply only when the spacecraft is outside of the magnetosphere, and that the nearly isotropic protons just within the magnetosphere boundary are not lethal for exposures over reasonable lengths of time. It is then highly probable that only those lunar probes that spent the major portion of their transit time to the moon in the region outside of the magnetosphere were the ones to receive doses of ionizing radiation sufficient to kill the majority of the exposed organisms residing upon them. Even for these lunar probes —although the solar wind possesses a local degree of anisotropy that the solar ultraviolet radiation does not — the number of organisms accessible to solar wind protons in excess of those organisms accessible only to solar ultraviolet should not be significant. Mainly for this last reason but also because of the large amount of uncertainty that exists, in the author's opinion, concerning the validity of current models of microbial death by ionizing radiation, the question of the times spent by the individual lunar probes outside the magnetosphere has not received attention in estimating the microbial burden at the time of impact of the probes on the moon.

Of course, there are other uncertainties associated with both ionizing and ultraviolet kill mechanisms. One already mentioned is the amount of shielding offered by dust particles on which the organisms might reside, or another possibility is that the organism could be located in microscopic pits or cracks in the spacecraft surface. Although there exists no concrete evidence by which this uncertainty could be resolved, it would seem that such shielding could be available to very few of the organisms because of the usually extensive cleaning of the surfaces prior to launch, the quality of the surfaces, and the small probability of lodging randomly distributed microorganisms in (presumably) randomly distributed cracks. The second point of uncertainty, the actual fraction of the surface area of each of the individual lunar probes exposed directly to sunlight, could be removed if data could be made available on the exact geometry of each craft and the orientation of each craft's axis of symmetry with respect to the sunward direction over the time of transit to the moon. Unfortunately, such data was not made available for this study. When it is presumed that the normal flight mode of each lunar probe is with solar panels extended and facing the sun, then a study of the available photographs and sketches of the vehicles suggests that, depending upon the vehicle geometry, 40 to 70 percent of the surface of the vehicles would be exposed. It should be mentioned that good photographs or drawings of the lunar probes in their flight configuration are lacking, particularly for the Soviet Union vehicles.

These conclusions are best summarized by describing the model that has been used to estimate the microbial burden on the several lunar probes just prior to impact on the moon. Let:

N_{Ie} (or N_{Le}) = the expected number of all viable exposed microorganisms on a given lunar probe just prior to impact (or just prior to launch).

S_{Ie} (or S_{Le}) = the expected number of exposed spores on a given lunar probe just prior to impact (or just prior to launch).

V_{Ie} (or V_{Le}) = the expected number of exposed vegetative cells on a given lunar probe just prior to impact (or just prior to launch).

Let the corresponding quantities, but with an "o" instead of an "e" subscript, N_{Io} or N_{Lo}, S_{Io} or S_{Lo}, V_{Io} or V_{Lo}, denote the expected number of occluded or embedded organisms of the stated kind at either launch or impact. Then obviously,

$$\begin{aligned} N_{Ie} &= S_{Ie} + V_{Ie} , \\ N_{Le} &= S_{Le} + V_{Le} , \\ N_{Io} &= S_{Io} + V_{Io} , \\ N_{Lo} &= S_{Lo} + V_{Lo} . \end{aligned} \tag{3.1}$$

Assume that, on the average, 50 percent of the surface of every vehicle is exposed to direct solar ultraviolet and that the spores are uniformly distributed over the surface. Then

$$S_{Ie} = \frac{1}{2} S_{Le} \tag{3.2}$$

for exposure times of at least 12 hours, since the radiation dose required to reduce spore populations by one decade is acquired in times relatively short compared with the typical flight time. (The fraction exposed, here set equal to 1/2, could be chosen to be different for each spacecraft if there were evidence to warrant it.) Also, since it appears that occluded or embedded spores are not vulnerable to thermal kill at typical temperatures,

$$S_{Io} = S_{Lo} . \tag{3.3}$$

On the other hand,

$$V_{Ie} = \frac{1}{2} V_{Le} \left(10^{-\tau/120}\right) , \tag{3.4}$$

where τ is the flight time in hours, and it has been assumed that the D value for vegetative cells under these conditions is about 120 hours and that the exposed vegetative cells are uniformly distributed over the surface. Again, the fraction 1/2 appearing in (3.4) could be made dependent upon the particular lunar probe geometry and flight orientation with respect to the sun. For the occluded and embedded vegetative cells,

$$V_{Io} = V_{Lo}\left(10^{-\tau/120}\right) \tag{3.5}$$

By using (3.1) through (3.5), the microbial burdens just prior to impact for each of the several lunar probes impacting the moon prior to July 1967 have been computed; these are shown in columns 4 through 8 in Table III. The at-launch values of the several categories of microbial burden required to obtain these estimates are those given earlier in Table I. The sources for the flight times shown in column 3 of Table III are References 31 and 32. Table III does not include probes which achieved "soft" landings on the lunar surface.

Although these estimates are rough and perhaps conservative in the sense of overestimating the number of survivors at impact, it is believed that the assumptions used to obtain them are the only reasonable ones that are consistent with current experimental evidence and, at the same time, with the uncertainties implicit in the estimates of viable microorganisms on the spacecraft just prior to launch. It has been suggested that all of the vegetative cells present at launch will be killed by thermal mechanisms during a 60-hour flight, leaving only the spore-formers present at impact [3]. The author does not believe that the data of, say, Silverman and Beecher [26], which most nearly applies to the combined set of conditions to be found in cislunar space, supports this point of view.

TABLE III

Estimates of the Microbial Burden Just Prior to Impact for Lunar Probes Known to Have Made a Hard Impact on the Moon Before July 1967

Lunar Probe	Impact Data	Flight Time (hours)	Estimated Total Burden ($N_{Ie} + N_{Io}$)	Estimated Exposed Spores (S_{Ie})	Estimated Occluded and Embedded Spores (S_{Io})	Estimated Exposed Veg. Cells (V_{Ie})	Estimated Occluded and Embedded Veg. Cells (V_{Io})
Luna II (U. S. S. R.)	1959 Sept. 13 21h02m23s	34	2.90×10^7	9×10^6	2×10^6	1.47×10^7	3.27×10^6
Ranger IV (U. S.)	1962 April 26 12h50m24s	64.01	2.39×10^7	9×10^6	2×10^6	1.06×10^7	2.34×10^6
Ranger VI (U. S.	1964 Feb. 2 09h24m33s	65.59	2.35×10^7	9×10^6	2×10^6	1.02×10^7	2.27×10^6
Ranger VII (U. S.)	1964 July 31 13h24m49s	68.60	2.28×10^7	9×10^6	2×10^6	9.65×10^6	2.14×10^6
Ranger VIII (U. S.)	1965 Feb. 20 09h57m	64.87	2.37×10^7	9×10^6	2×10^6	1.04×10^7	2.30×10^6
Ranger IX (U. S.)	1965 March 24 14h08m20s	64.52	2.37×10^7	9×10^6	2×10^6	1.04×10^7	2.30×10^6
Luna V (U. S. S. R)	1965 May 12 19h10m	83.23	1.99×10^7	9×10^6	2×10^6	7.26×10^6	1.61×10^6
Luna VII (U. S. S. R.)	1965 Oct. 7 22h08m24s	86.22	1.94×10^7	9×10^6	2×10^6	6.88×10^6	1.53×10^6
Luna VIII (U. S. S. R.)	1965 Dec. 6 21h51m30s	82.06	1.99×10^7	9×10^6	2×10^6	7.31×10^6	1.52×10^6
Luna IX (U. S. S. R.)	1966 Feb. 3 (1:45 EST)	79	2.07×10^5	9×10^4	2×10^4	7.92×10^4	1.76×10^4
Surveyor I (U. S.)	1966 June 2 (1:17:37 EST)	63.6	1.0×10^5	2.25×10^4	5×10^3	5.96×10^4	1.32×10^4
Lunar Orbiter I (U. S.)	1966 Oct. 29	~1920	2.47×10^3	2.47×10^3	5×10^1	(0)	(0)
Surveyor II (U. S.)	1966 Sept. 23	~62.8	6.29×10^5	5.5×10^2	4.89×10^4	6.6×10^3	5.73×10^5
Luna XIII (U. S. S. R.)	1966 Dec. 24	~79.7	2.06×10^6	9×10^5	2×10^5	7.81×10^5	1.74×10^5
Surveyor III (U. S.)	1967 April 19	~63	1.52×10^6	2.25×10^2	4.96×10^4	5.55×10^3	1.46×10^6

IV. DISPERSAL OF MICROORGANISMS UPON THE HARD IMPACT OF A SPACECRAFT ON THE MOON'S SURFACE

Possible Mechanisms of the Dispersal

The atmosphere of the moon is apparently very thin. From measurements of the lunar occultation of the Crab Nebula, a strong cosmic radio source, it has been estimated that the surface density of the lunar atmosphere is about 2×10^{-13} of the earth's atmosphere at normal temperature and pressure [33]. If such an estimate is correct to within even a few orders of magnitude, then it is clear that the usual mechanisms of the long-range transport of small airborne particles which prevail in the earth's atmosphere—convection by winds, and diffusion—should be almost entirely absent on the moon. A small, uncharged particle given an outward velocity at a point near the moon's surface should then have a motion which is changed mainly by lunar gravity and hardly at all by drag effects. On the other hand, and precisely because of the weakness of drag forces and the low gravity of the moon, such a particle would in general travel much farther from the point of release on the moon than it would if released with the same velocity on earth.

The motion of a charged particle near the lunar surface would certainly be influenced by a lunar electrostatic field if it existed and was of sufficient strength. Estimates have been made of the surface potential of the moon and some of these are as high as 20 to 25 volts [34], but to the author's knowledge these estimates have no direct background in observational evidence. The main sources of the electric charge furnishing a lunar electrostatic field are presumably the proton and electron streams from the sun, secondary electrons resulting from the solar particle flux, and photoelectrons produced by solar ultraviolet and X-radiations. Although all of these sources must maintain an average charge neutrality near the surface of the moon, it is possible that local statistical fluctuations in the solar particle streams and the processes that produce secondary charged particles will produce local and perhaps quite ephemeral electric fields. The motion of an extraneous charged particle in such nearly random electric fields is obviously unpredictable. It seems reasonable at this point to assume that the effects of lunar electric

fields on the motion of a charged particle average to zero. New evidence may, of course, require that this assumption be changed. It is inevitable that a certain amount of charging will occur on the spacecraft debris and crater ejecta formed in a hard impact, and it is known that certain microorganisms show a net negative charge. The question of lunar electric fields will be taken up again later where the concern will be with the possible mechanisms of transport of microorganisms after their initial dispersion upon impact.

The lunar magnetic field with an intensity less than 5×10^{-4} gauss [35] is obviously too weak to effect the motion of charged dust grains having the maximum possible charge-to-mass ratio. Grannis has estimated the maximum charge-to-mass ratio for a 5-micron diameter sphere of silica and has found a value of about 8.96×10^{-7} e.s.u/gm [36]. Thus, the effects of any lunar magnetic fields on the motion of crater ejecta should be wholly negligible.

It is therefore possible to conclude that, in the absence of strong, extensive electric fields on the moon's surface, an element of debris or crater ejecta formed in the hard impact of a lunar probe will be dispersed along a ballistic trajectory determined by the initial speed and angle of ejection. For reasons discussed later, it is also possible to conclude that the dispersal upon impact is by far the major part of the transport of material away from the impact site.

The notion of hard impact has already been mentioned several times and should be defined. For the present purposes, a hard impact will be regarded as any impact at velocities exceeding lunar escape speed (2.38 km/sec). Of course, impacts at speeds considerably less than escape speed could result in fragmentation of the projectile and the extensive spreading of crater material. But fortunately, it is not necessary to consider impacts at such intermediate speeds. The data for impact speeds of the lunar probes reaching the moon seems to fall into two extremes: either a spacecraft fell into the moon with a speed of 2.60 to 2.68 km/sec, or a soft landing was made at a speed not exceeding the design limits of the craft, nominally 4 to 6 m/sec. Exceptions to this data are the Luna II booster which is known to have impacted on the moon, but whose impact coordinates and speed remain unknown, and the Surveyor D (IV) which, as far as the author can tell, may have made a hard impact or may have disintegrated above the moon's surface.

The impact dispersal of spacecraft fragments and the material from the crater that is formed in the impact have obvious relevance to the scattering of microorganisms since: (a) Microorganisms may remain attached to the fragments of the craft and thus travel with the fragments to possibly large distances from the point of impact, or (b) the microorganisms may be separated from the surfaces of the spacecraft during impact and then become entrained in the crater debris cloud. It is possible to imagine still other means by which the organisms are dispersed: (c) Microorganisms may be directly ejected from the surfaces to which they are attached by the action of impulsive forces occurring prior to and during impact, and (d) some fraction of the microorganisms contained in the retro-rocket fuel is dispersed by means of the exhaust plume at landing.

The range and lateral spread pattern of retro-rocket fuel residues deposited on the lunar surface near the landing site has received some study [1]. The extent of the fuel residue pattern obviously depends upon the altitude of the craft above the surface when the retro-rockets are brought into use and somewhat upon the geometry of the rocket nozzles and the orientation of the nozzle centerlines with respect to the vertical direction. The number of living cells deposited with the residues must also depend upon the initial number of cells occluded in the fuel and the resistance of these cells to the shock of combustion. Since there is considerable uncertainty concerning all of the factors mentioned above for the particular lunar probes that are known to have impacted the moon, an assessment of the degree of dispersal afforded by retro-rocket exhaust plumes cannot be made in any reasonable way. For soft landings, such dispersal is likedly to provide the major mechanism of dispersal of microorganisms; however, the absolute number of organisms deposited by each lander in this way should be small (because of the relatively small number of organisms believed to be initially embedded in the fuel). On the other hand, it is safe to say that in those instances where a retro-rocket was initiated before a hard impact, the contribution to the lunar contamination presented by the exhaust residues represents but a small part of the contamination caused by other mechanisms that will be discussed presently.

Very little can be said about the possibility of the direct ejection of organisms from the lander surfaces by the action of impulsive forces. A spacecraft impacting the moon's surface at a speed of about 2.6 km/sec and coming to rest in a distance of 2 meters or less will experience a deceleration of about 10^5 g. Neglecting for the moment the possibility of other impulsive forces (such as those induced by shock or stress waves propagating along structural members of the craft), the inertial forces acting during the abrupt

deceleration at impact upon a particle attached to a surface of the craft could detach the particle if the bonding force between the particle (a microorganism or a grain carrying microorganisms) and the surface could be overcome. The residual momentum of the detached particle would then be mainly in a forward direction and the particle would be cast into the nascent impact crater. Thus, the deceleration at impact would, in the absence of large transverse accelerations, be insufficient to directly scatter the microorganism or grain beyond the crater. This does not mean that the particle would remain in the crater, for there is a definite possibility that the particle becomes entrained in the powdered crater debris flowing outward between the projectile debris and the walls of the crater. A second method whereby organisms may become entrained in crater debris is if particles adhering to the exposed surfaces of the craft could be "scrubbed off" by the crater dust. These are possibility (b) mentioned in an earlier paragraph. The point is that direct ejection by inertial forces caused by impact deceleration does not seem possible unless the breakup of the spacecraft during impact is such that large, transverse, impulsive forces are generated.

Although it is believed to be of minor importance, the possibility of direct ejection of organisms cannot definitely be ruled out since there is a lack of knowledge of the breakup dynamics of the spacecraft. The problem to be faced in actually deciding the importance of direct ejection could be circumvented if something were known about the adhesion of microorganisms (or dust grains carrying microorganisms) to various surfaces, and in particular, the types of surfaces normally exposed at impact. The standard theory of van der Waal's attraction gives some means of estimating these forces of adhesion, but only under very ideal conditions (such as clean, polished surfaces, spherical particles, no electric charge, and such). For instance, it is known that the acceleration (in g) required to remove a quartz sphere of diameter d (cm) from a flat quartz plate is approximately $0.202/d^2$ [37]. A 10^5 g deceleration would remove spherical quartz particles having diameters greater than 14 microns under these ideal conditions. However, it is also known that there is a large variation in the force required to remove small dust particles from an arbitrary surface when such factors as particle size, surface roughness, coating by films, and electrostatic effects are not so well controlled. For bare microorganisms, the removal force is known to be large [38], but then environmental microbiologists believe that viable organisms are more often found attached to particulate matter than in a solitary, unprotected state.

In view of this present lack of knowledge concerning the adhesion of small, irregularly shaped particles to typical spacecraft surfaces and the exact role these particles might play in the transport of viable microorganisms, one is forced to consider two idealized, alternative mechanisms for the dispersal of microorganisms upon hard impact. These two alternatives are strong forms of the possibilities (a) and (b) mentioned earlier, namely:

(a) All microorganisms residing on the spacecraft remain attached to a spacecraft during and after the impact.

(b) All microorganisms residing on the spacecraft become detached during impact and are uniformly entrained in the cloud of crater material ejected during the impact.

A consequence of (a) is that the dispersion pattern of the spacecraft fragments determines the dispersion of microorganisms, and a consequence of (b) is that the dispersion of the crater debris controls the scattering of the organisms. That these alternatives are extremes of the possible mechanisms of dispersal is quite obvious, if one disregards (as we shall) the possibility of direct ejection and escape of some of the organisms. Since these alternatives are extremes, it is possible that they might furnish some idea of the limits upon the expected contamination of the moon's surface—contamination being regarded here as the density of organisms at any given distance from an individual impact site. With either one of these alternative dispersal mechanisms, a living organism could receive some protection from harmful ionizing and ultraviolet radiations while being carried possibly large distances from the impact site. Each of the alternatives, (a) and (b), will now be examined in detail.

Transport of Microorganisms Attached to Spacecraft Fragments

In this part of the present section, the consequences of the assumption that all organisms remain attached to the spacecraft during and after hard impact will be explored. As was stated earlier, such an assumption has the immediate consequence that the dispersion pattern of the fragments determines the contamination of the lunar surface about the impact site by microorganisms residing upon the spacecraft.

Appendix C contains an attempt to calculate the range distribution of the fragments of a spacecraft that makes a hard impact on the moon. The calculation has been applied to three hypothetical impacts that differ mainly in the mass of the object striking the moon. The parameters for each of these cases are listed in Table IV.

TABLE IV

Sample Case Parameters for Fragment Range Distribution

Case	Object Mass (kg)	Impact Speed (km/sec)	Number of Fragments
1	100	2.60	5×10^4
2	365	2.64	5×10^4
3	1550	2.60	5×10^5

In each of the cases it has been assumed that the minimum fragment mass is 0.3 gm and that the fraction of the impact energy going into residual kinetic energy of the fragments is 1.1×10^{-4}. Reasons for the choice of these parameters are given in Appendix C.

Figures 1 through 3 show the results of the calculation for the three sample cases mentioned above. The ordinate in these figures gives the probability, P(s), that a fragment ejected during the impact will travel a distance no greater than s kilometers, while the abscissa is the distance, s, in kilometers. It is immediately evident from these results that 97 percent or more of the fragments produced in the impact will be found within 10 km of the impact point in each case. The probabilities for fragment dispersal at several selected distances along the surface of the moon are shown in Table V for each of these three cases in order to extend the curves in Figures 1 through 3.

TABLE V

Table of P(s) for Several Values of s not Less than 10 km

		s (kilometers)				
Case		10	50	100	250	500
1		0.9956159599	0.9999990190	0.9999999999	-	-
2	P(s) =	0.9758137700	0.9995780067	0.9999977432	0.9999999999	-
3		0.9905723584	0.9999833329	0.9999999984	-	

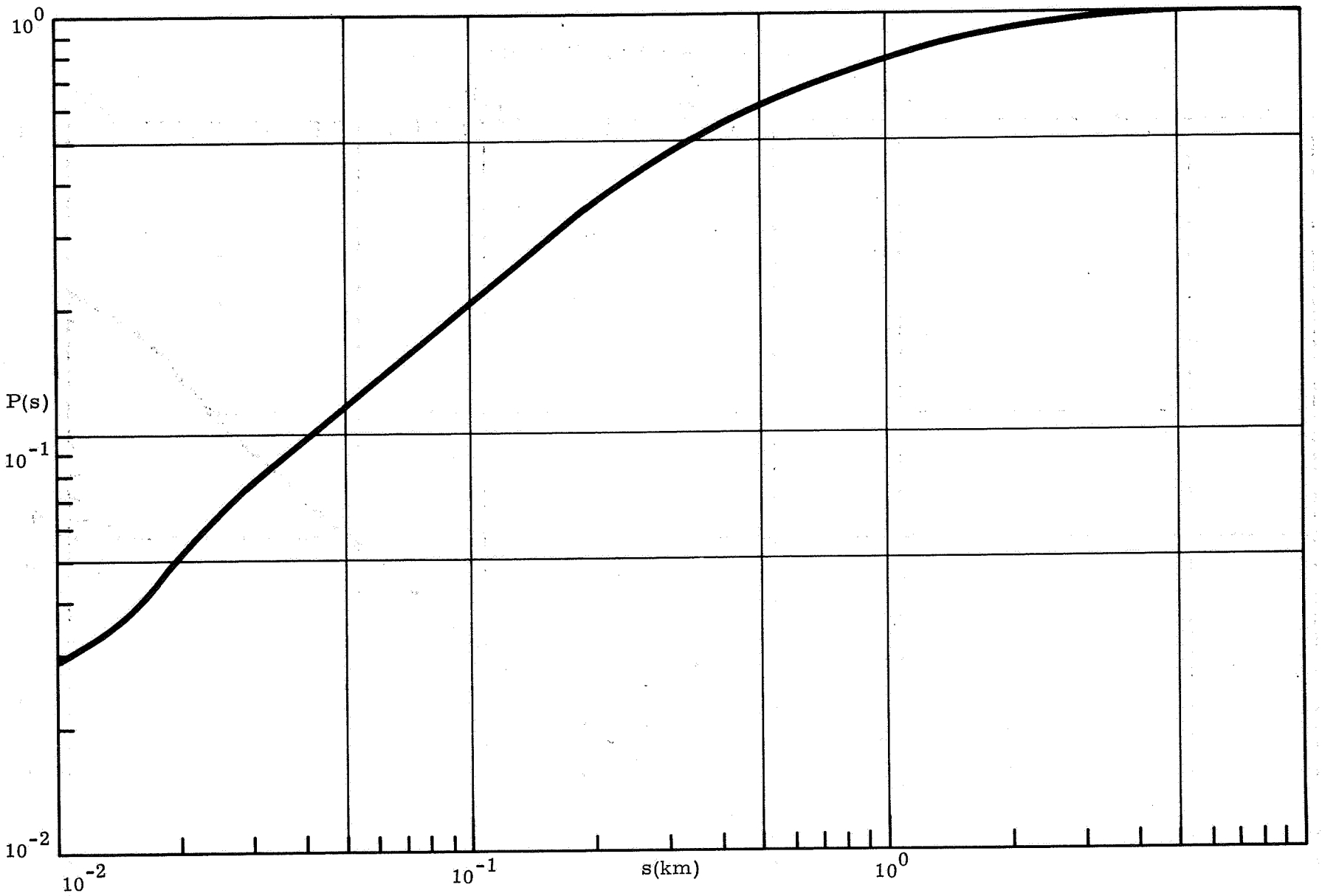


Figure 1. Case 1 Parameter Values

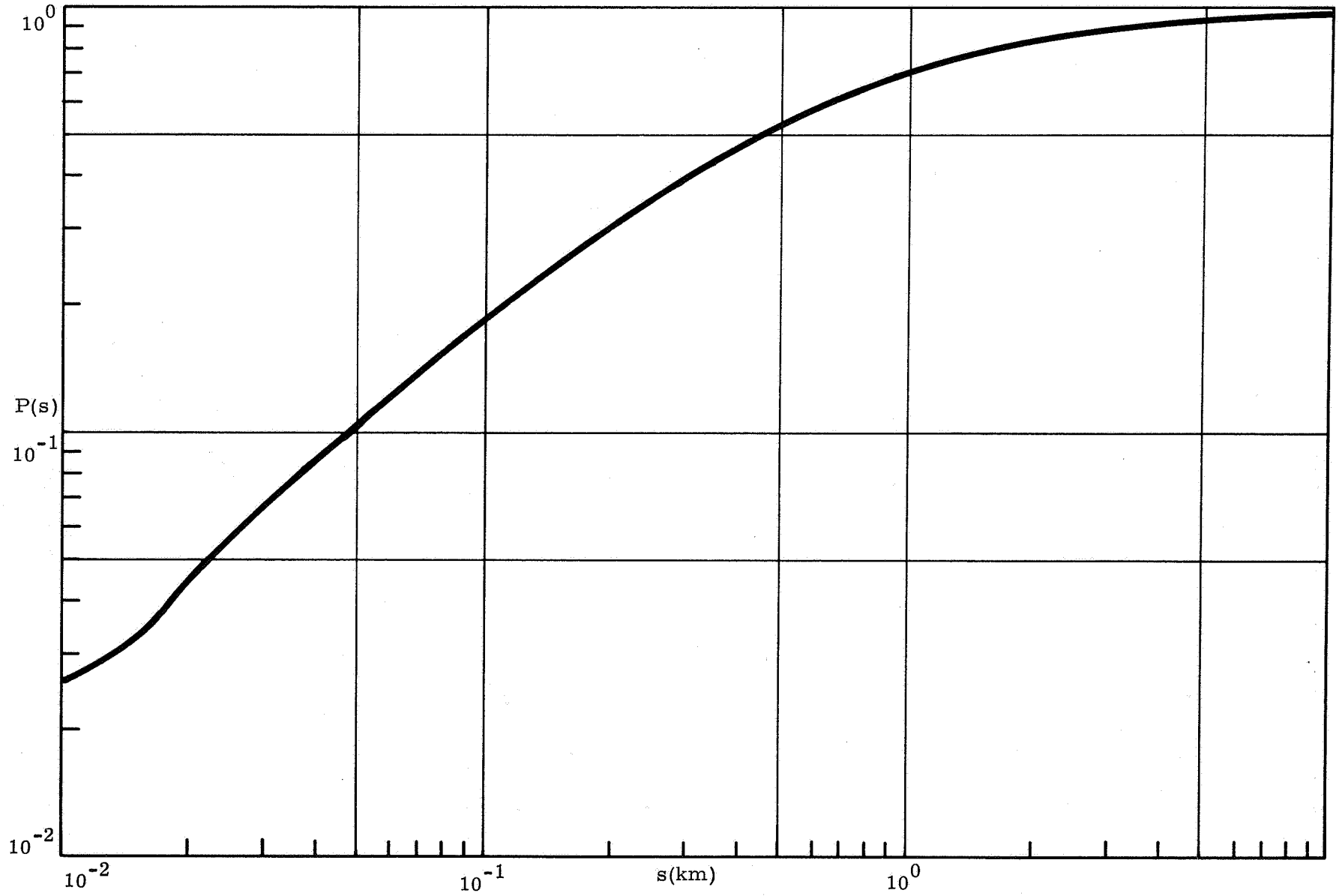


Figure 2. Case 2 Parameter Values

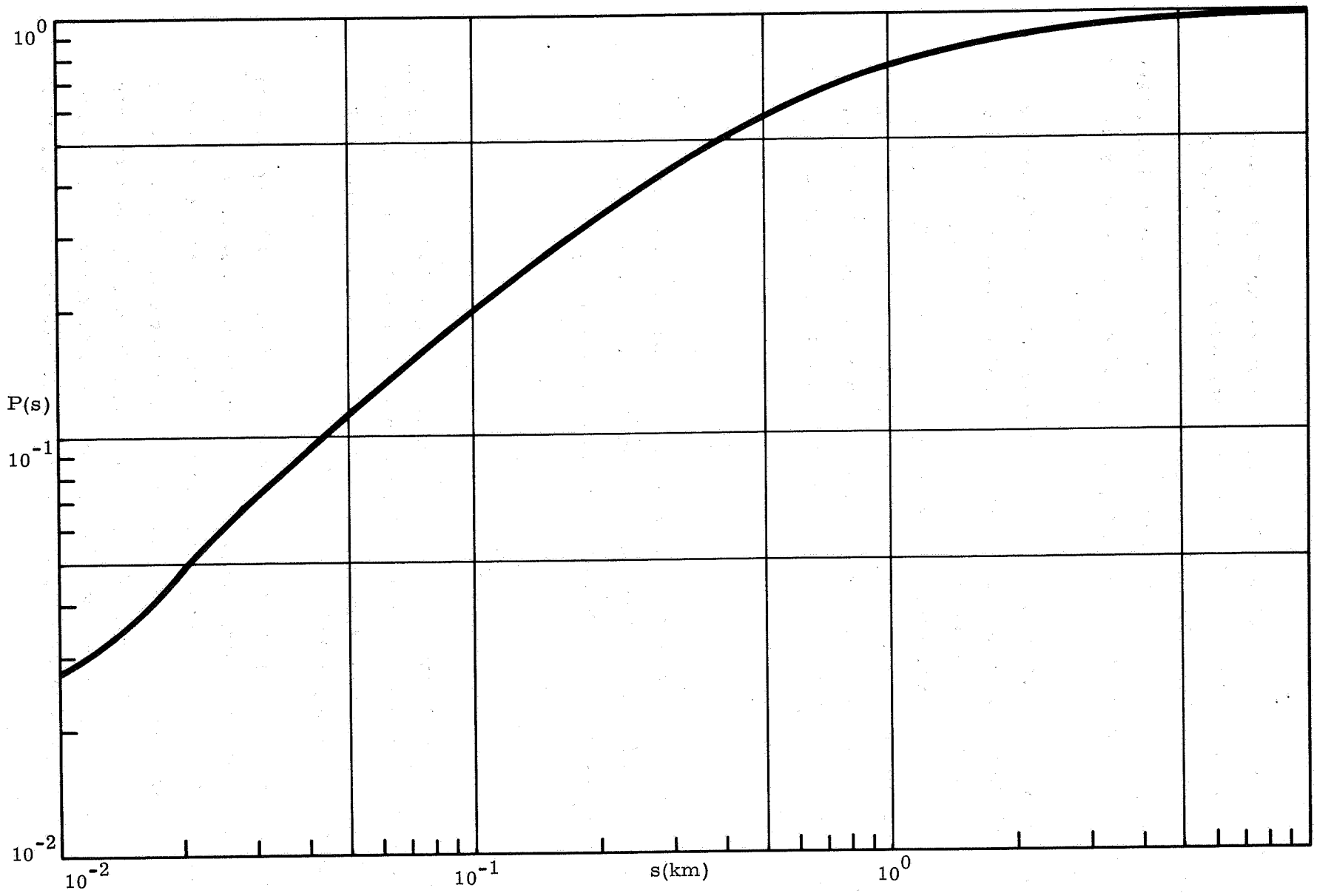


Figure 3. Case 3 Parameter Values

The dash in the last two columns of Table V is intended to mean that P(s) exceeds 0.9999999999, or in other words, that the chance of a fragment being cast beyond s kilometers is less than 10^{-10}. The probabilities in Table V show that virtually all of the fragments in each of the three hypothetical cases should be contained within 50 km of the impact point (in the sense that the expected number of fragments cast beyond 50 km is of the order of one).

The implications of these results for the contamination of the moon by microorganisms are clear enough if one does not insist upon a close, quantitative interpretation of them. If all the organisms remain attached to the spacecraft fragments, then the chances of retrieving an organism deposited by that particular spacecraft outside of 50 km from the impact point are virtually zero. Within 10 km of the impact point, the probability of retrieving one or more organisms is essentially the probability that one or more fragments are retrieved. The latter quantity can be roughly estimated from the formula:

$$1 - \exp[-A\Phi(s)]$$

where A is the surface area of the patch of lunar soil to be sampled in units of km^2 and $\Phi(s)$ is just the expected density of fragments (No./km^2) at a distance of s kilometers from the impact point. For s less than 10 km, $\Phi(s)$ may be approximated by

$$\frac{N_f}{2\pi s} P'(s)$$

where N_f is the number of fragments formed in the given impact, and P'(s) is the derivative of the range distribution of fragments. Table VI shows such estimates of the probability of retrieval of one or more fragments for the three hypothetical impacts listed in Table IV when A = 1 m^2 and $N_f = 10^5$.

The probability of retrieval of one or more fragments should actually depend upon the depth of the sample of lunar soil in addition to the surface area of the sample, for fragments may penetrate the first few centimeters of the lunar crust and it is entirely possible that by merely skimming the surface, no fragments would be retrieved although the subsurface density could be large. On the other hand, it is possible that organisms could be dislodged or "rubbed off" as the fragment penetrated the surface layer; in this case the depth-dependence of the probability of retrieval becomes even more difficult to

guess. (Admittedly, the introduction of the possibility of "rub-off" of organisms is inconsistent with the original assumption that all of the organisms remain on the spacecraft or a fragment of it.) In addition to these complications, any attempt to find the probability of retrieval of organisms transported on fragments should take into account the distribution of the organisms over the fragments or, in other words, the probability that there may be one or more organisms on a fragment, given that the fragment is retrieved in a sample of a certain size. If it is assumed that the organisms remaining alive at impact are uniformly distributed over the surfaces of the craft, then this latter probability is always 1 provided that the size of the viable organism population at impact exceeds the number of fragments. A uniform surface distribution of the remaining, living organisms at the time of impact seems improbable, however, in view of the discussion of organism die-off in space given earlier.

TABLE VI

Estimates of the Probability of Retrieval of One or More Fragments at Distances No Greater than 10 km from an Impact Point for a 1 m^2 Sample Area

Case	1 km	2 km	4 km	6 km	8 km	10 km
1	1.99×10^{-3}	2.99×10^{-4}	3.18×10^{-5}	5.84×10^{-6}	1.27×10^{-6}	9.10×10^{-7}
2	1.99×10^{-3}	2.99×10^{-4}	4.78×10^{-5}	1.26×10^{-5}	4.50×10^{-6}	3.22×10^{-6}
3	1.59×10^{-2}	2.99×10^{-3}	3.98×10^{-4}	8.77×10^{-5}	2.42×10^{-5}	1.74×10^{-5}

None of the complications just mentioned would, if taken into account, increase the estimates given for the examples in Table VI. Within the limitations of the method we have used to calculate the fragment dispersal, it should be evident that the transport of organisms by fragments would give negligible potential contamination of the lunar surface beyond 50 to 60 km from the impact point for all of the impacts of unmanned lunar probes which are known to have occurred.

Transport of Microorganisms by Entrainment in the Crater Debris

In contrast to the assumption just made, we will further assume that all microorganisms are somehow removed at impact and become attached to grains of the crater debris. Since up to one-half of the kinetic energy expended in the impact may go into

kinetic energy of material ejected from the crater, it is at once obvious that such an assumption will lead to a distribution of contamination about the point of impact that is considerably different from the distribution considered previously. Of course, it is as unrealistic to assume that all organisms residing on the lunar probe are removed during the shock of impact as it is to assume that the organisms are retained on the fragments of the craft. Whether or not an organism or a grain carrying organisms is removed at impact depends upon the forces acting on it during the breakup of the spacecraft, as has been mentioned previously. It is highly improbable that all material points in the structure of the craft at which viable organisms are deposited will experience forces sufficient to dislodge those organisms; even if such was possible, it is still more improbable that all of the organisms would find pathways out of the mass of spacecraft fragments and would become attached to crater dust in the short time available (about 1 msec). But it is just these improbabilities that suggest that the assumption of total removal and entrainment in the debris cloud is conservative, and estimates of the dispersion of organisms made on the basis of this assumption should lead to overestimates of the chances of finding an organism at large distances from the point of impact. We believe that such a conservative point of view that takes into account some of the physical constraints should lead to more realistic upper bounds on the expected number of organisms to be found at a given distance from the impact point of a lunar probe than the point of view that assumes that all organisms are uniformly distributed over the surface of the moon.

In Appendix D, an attempt has been made to calculate the amount of lunar soil ejected by a spacecraft making a hard impact on the moon, and the dispersion pattern of that ejected material in terms of the number of grams of ejecta deposited per square kilometer centered at a given distance from the impact point. The calculation assumes that the moon is a perfectly smooth sphere and that the motion of the material is influenced only by lunar gravity. Other, possibly equally inexact assumptions are made, and these are discussed in Appendix D. However, it is believed that nothing has been assumed which does not have some justification in terms of physical evidence or which would lead to the making of underestimates of the surface density of organisms at some given distance from the impact point (although the assumption of a perfectly smooth moon might be an exception to this claim for rather obvious reasons).

The calculational scheme developed in Appendix D has been applied to the three examples employed previously which seem to bracket the conditions for the known, hard impacts of lunar probes on the moon. The results are shown in Figures 4 through 6, which give the surface density of crater ejecta in grams per square kilometer [denoted $\sigma(s)$]

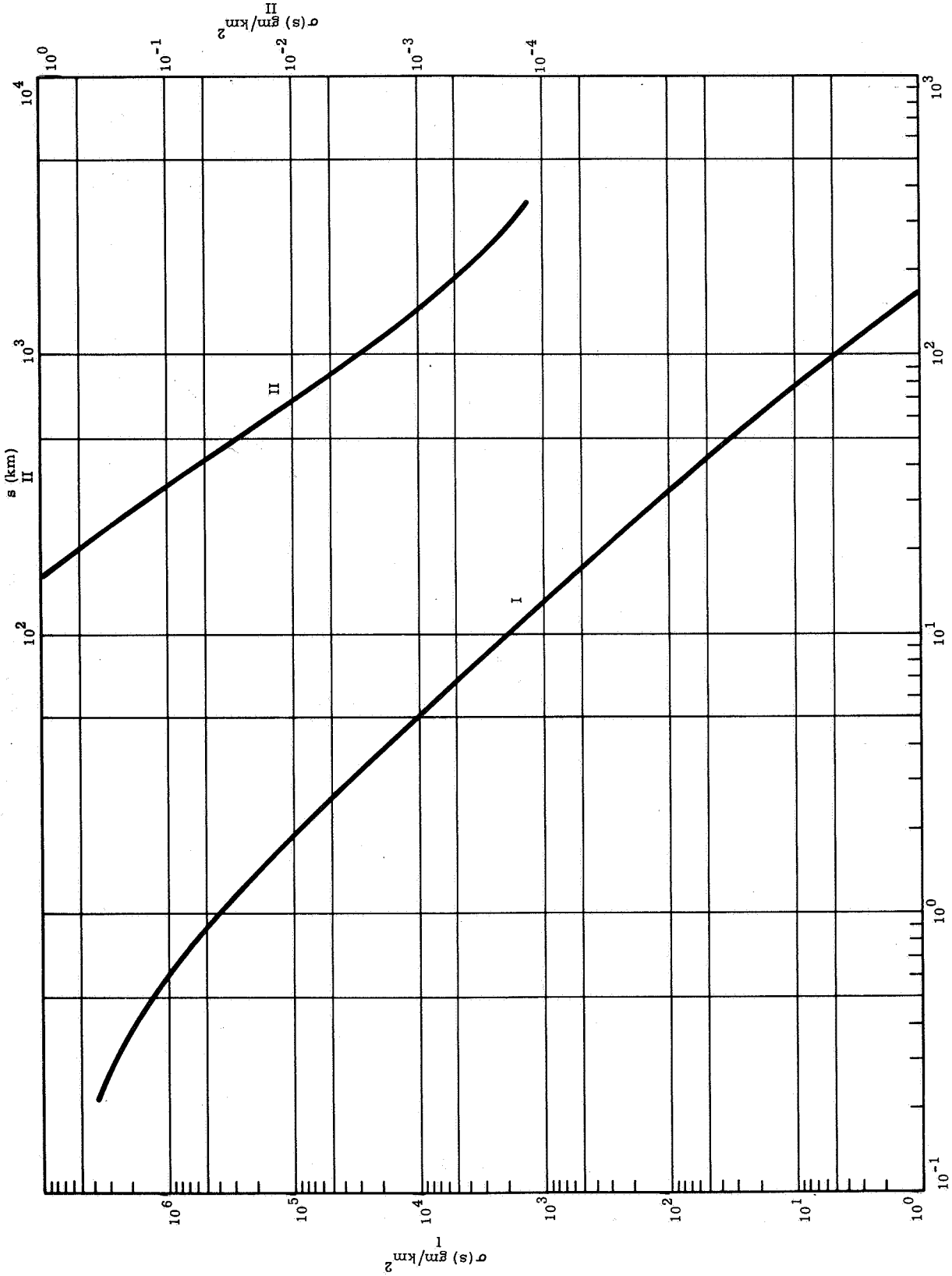


Figure 4. Case 1 Parameter Values

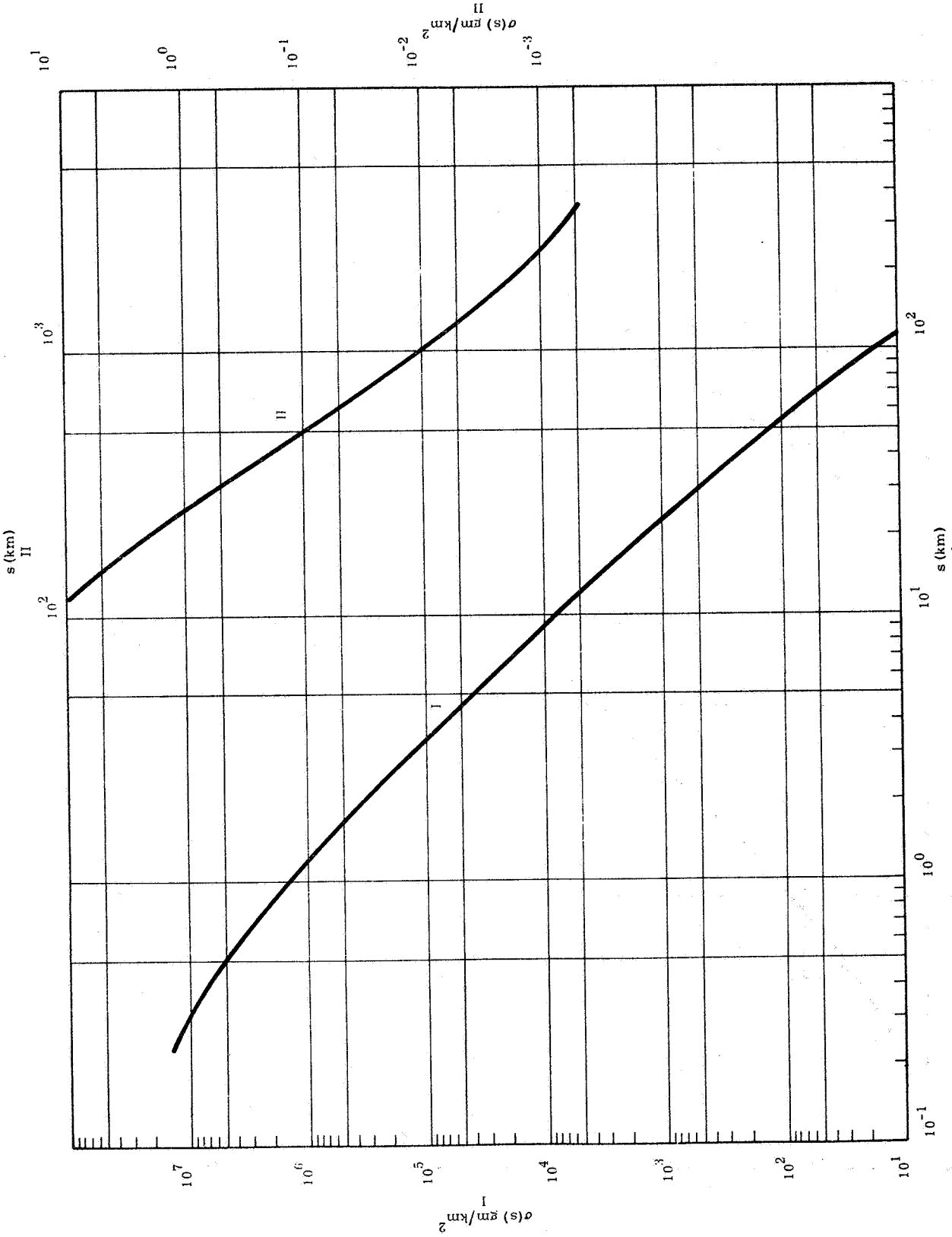


Figure 5. Case 2 Parameter Values

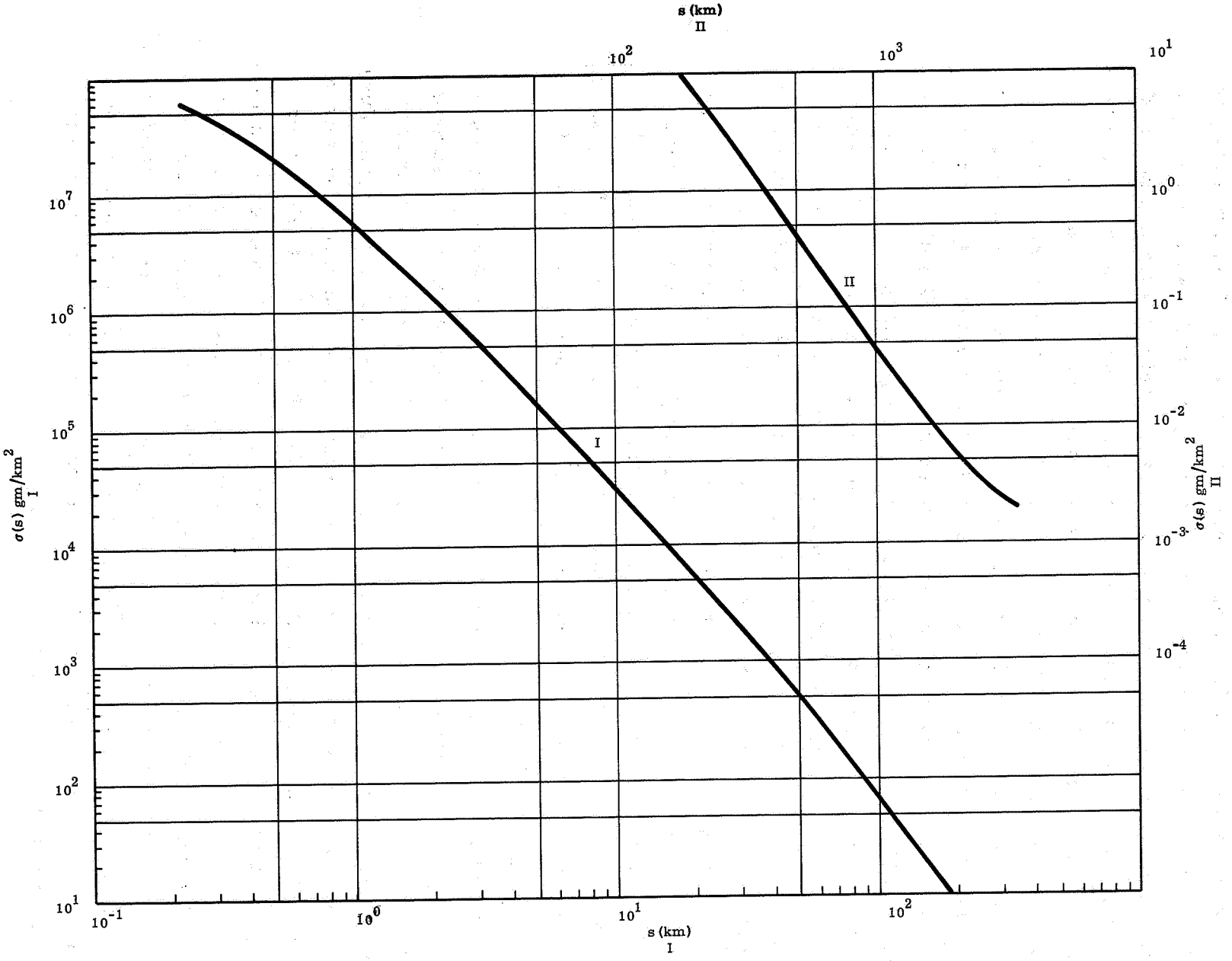


Figure 6. Case 3 Parameter Values

as a function of the distance in kilometers from the impact point. These curves may be easily used to estimate the expected number of microorganisms that would be found per unit area at some given distance from an impact point, provided that the assumption of complete detachment of all organisms and subsequent uniform mixing in the crater debris cloud is considered valid. To illustrate this point, consider the several spacecraft of the Ranger series that are known to have made hard impacts on the moon. The mass of each of these craft was about 365 kg and the impact speed was about 2.64 km/sec. The mass of lunar soil ejected from the impact crater of a Ranger would be approximately 4.8×10^7 gm according to the formula given in Appendix D. Table III indicates that the estimated, total burden of viable microorganisms for a Ranger just prior to impact would be about 2.4×10^7 organisms. Uniform mixing of these organisms in the crater material would then lead one to expect the presence of one organism in every 2 gm of crater material (or 0.5 organism/gm). One may now use Figure 5 to gain some idea of the distribution of organisms around a Ranger impact site and, as a consequence, to derive a rough estimate of an upper bound to the probability of contamination of a sample of lunar soil by a viable microorganism of terrestrial origin. The ordinate of Figure 5 gives $\sigma(s)$, the density of crater material in grams/km^2 to be found at a distance of s kilometers from the impact site. Multiplying $\sigma(s)$ by 0.5 organism/gm will then give the expected number of organisms to be found in a 1 km^2 area centered at a distance of s kilometers from impact point.

To carry the illustration a bit further, we pose the following problem. Suppose a sample of the lunar soils is to be retrieved by removing a layer of soil 1 m^2 in surface area and several centimeters in depth. (As it will turn out, the depth of the volume removed should not be important for considerations of contamination by crater ejecta which may carry microorganisms.) What should be the distance of the site of retrieval from a Ranger impact site if one desires, at the most, a probability of 10^{-6} of finding one or more organisms from that particular Ranger in the soil sample? The answer to the question can be found from Figure 5 and by converting the ejecta density into a density of organisms as described in the previous paragraph. At 150 km from the impact site, the ejecta density amounts to 2 gm/km^2 or, converting to an organism density, 1 organism/km^2 which yields an expected number of 10^{-6} organism/m^2. If a 10 cm^2 area were sampled, one could move to a point within about 18 km from the impact site; a 1 cm^2 area sample could be taken at about 7 km from impact.

It may also be of interest to compute the distance from the Ranger impact site at which the expected density of organisms on the moon's surface obtained according to the sample calculations with Figures 4, 5, and 6 is equal to the density of organisms that would be obtained if, as it has sometimes been assumed, the organisms were uniformly spread over the entire lunar surface. Since the area of the moon's surface is about 3.8×10^7 km^2, and it has been assumed that Ranger carried 2.4×10^7 viable organisms, a uniform distribution would give 0.63 organism/km^2, which translates into a distance of 240 km from the impact site according to Figures 4, 5, and 6 and the assumption of uniform mixing of the organisms in the ejecta from the crater. Thus, for this particular example, it could safely be said that the assumption of uniform spread of the organisms over the surface is a conservative one outside of 240 km from the impact site, while within 240 km, the assumption could be misleading according to the considerations given above. Similar calculations and arguments can be made for the "safe" distance from impacts different from the hypothetical Ranger impact used in the examples.

It should be clear that several potentially important effects have been disregarded in the simple examples given above. First of all, the contributions to the expected surface density of microorganisms at a given point on the moon's surface from impact sites other than the one under consideration have been assumed to be negligible (and one might now expect that such an assumption would be a good one if the impact sites were separated by distances of the order of 200 to 300 km or more). Also, the survival of the organisms after their initial dispersal at impact has not been taken into account. It is to be expected that even if the dispersed microorganisms are protected from ultraviolet and ionizing radiation by dust grains, some thermal kill will result over the passage of time. These matters will be given consideration later.

V. THE SURVIVAL OF MICROORGANISMS ON THE MOON

The Possibility of Transport of Microorganisms After Their Deposition by Impact

The picture of the dispersal of spacecraft material upon landing or impact that has been presented in Section IV would clearly be of little value if it were known that small particles could be rapidly transported over the lunar surface by mechanisms naturally present on the moon. As was mentioned earlier, such mechanisms could not depend on the existence of a lunar atmosphere but could depend upon electrostatic fields or the agitation of the upper layers of the lunar soil by meteor bombardment. The flow of lightly compacted material down a slope under the action of the moon's gravity is, of course, a certain candidate for a transport mechanism, although not a very important one for the present purposes because of the small average slope of the terrain in the Maria regions where most lunar probes have landed.

Transport mechanisms requiring an electrostatic field have been proposed by Gold [39] and by Grannis [36]. Gold's proposal requires only that the lunar surface be positively charged to a degree that a similarly charged grain on the surface will "hop" about—the direction of the hopping motion being preferentially downhill on a slope. In a study of Gold's proposal (and in a presentation of his own ideas) Grannis was able to show that the rate of mass transport due to electrostatic hopping on a slope of 6 degrees would be of the order of 10^{-10} gm/cm-sec. With such a mass transport rate, and by assuming a ratio of roughly 2 gm of small particulate material/organism (according to the example discussed in Section IV), it will be seen that the transport rate of microorganisms attached to dust grains would be insignificant in comparison with the mean lifetime of the organisms—especially under the harsh conditions on the moon. Grannis proposes another mechanism that bears similarities to Gold's but requires that the small, positively charged particles be raised above the surface by some means so that they may "coast" downhill while being held up by space charge effects. The means required to levitate the particle could easily be supplied by either the "hopping" of the grain or, more likely, by micrometeoroid bombardment. Weil [40] suggests that this transport by levitation could be

two orders of magnitude more effective than the transport due to the hopping mechanism alone. Nevertheless, the rate of transport of microorganisms attached to the grains would still be too slow to make significant changes in the deposition patterns even over hundreds of years.

The stirring of the surface layers of the moon by micrometeoroid bombardment might alone be sufficient to change the initial deposition patterns in shorter periods of time. In order that a substantial momentum be transferred to an organism-bearing grain, the mass of a micrometeoroid must exceed the average mass of a grain and the impact of the meteoroid must occur sufficiently near the location of the grain. To make a rough estimate of the order of magnitude of this effect, assume there is one organism-bearing grain per square meter (or 10^6 organism/km^2) and that the grains have a mass of 10^{-9} gm (corresponding to a mean diameter of 10 microns and a density of 1.5 gm/cm^2). The number of micrometeoroid impacts per square meter in 1 second for meteoroids having mass in excess of 10^{-9} gm has been estimated to be of the order of 10^{-2} [40] and, because of the form of the meteoroid mass distribution spectrum, it is reasonable to suppose that the majority of momentum-transferring impacts are with the smallest meteoroids, i.e., of 10^{-9} gm mass in the present case. Next, suppose that such a micrometeoroid must strike the surface within 1 mm of the organism-bearing grain (or about 1000 mean grain diameters—which is certainly generous) before any significant amount of momentum is transferred. With these assumptions, an easy calculation shows that the expected rate of momentum-transferring collisions of micrometeoroids with an organism-bearing grain is 10^{-8}/sec. In other words, a dust grain carrying a microorganism could be expected to be dislodged by a micrometeoroid once in about every 3 years. Again, we will find that such a mechanism is slow in comparison with the mean lifetime of an organism on the moon's surface, especially since any reorientation of an organism-bearing grain could expose the organisms to the solar particle and ultraviolet radiations.

In the absence of more extensive observational evidence of the phenomena of dust transport on the moon, it is believed that there should be no means of transport of <u>viable</u> microorganisms on the moon after their initial deposition by impact such that the initial deposition patterns would be changed significantly over the interval of time allowed to the lunar exploration program (as it is presently conceived).

Thermal Kill of Microorganisms on the Moon

In Section IV, it was assumed that all the viable organisms residing on a lunar probe at impact either were detached and extrained in crater dust or remained on the fragments of the craft. As was pointed out, in both of these idealized mechanisms of impact dispersal the organisms would possibly receive protection from harmful effects while being dispersed. It is obvious that after impact dispersal, no less a degree of protection from all but harmful thermal effects would be offered by the lunar soil. Fragments carrying organisms may penetrate the surface and come to rest at depths of up to 20 cm depending on the local depth of the dust layer at the point of fragment impact. The same is true for impact crater fragments having mass much larger than the mean mass of a lunar dust grain. Dust from impact craters, after it has settled, would be sufficient to protect at least one-half of the organisms attached to it since very little absorber is needed to effectively shield from the solar protons and ultraviolet radiation. Thus, only thermal effects and the presence of a high vacuum on the moon's surface would appear to have the potential for substantially decreasing the number of viable microorganisms after their initial deposition.

The temperature variation in the first few microns of lunar soil over a lunar day is fairly well known. The maximum temperature at a point near the center of the lunar disc at full moon is around 400°K while the minimum temperature falls to about 120°K on the dark hemisphere [41]. Local irregularities in the thermal properties of the surface or features underlying the surface may introduce fluctuations of as much as 10 percent about the average maximum and minimum values. The surface temperature variations at high lunar latitudes are less extreme. However, it is clear that any microorganisms deposited in the uppermost layer of dust grains of the moon's crust, and within 30 degrees of the equator, should experience temperatures in excess of 60°C for 120 to 144 hours of each diurnal cycle. Also, near the moon's surface the vacuum is almost certain to be as hard as the vacuum in free space near the moon. A consequence of these conditions would be that practically all <u>vegetative</u> cells brought to the moon by a typical lunar probe would die in a few lunar days or less, provided they were exposed to the vacuum. Of course, those organisms that are exposed to direct sunlight will perish in a matter of minutes. For <u>spores</u>, the rate of kill in a shielded state (yet one that has access to the high vacuum and the typical surface temperatures) would not be so large. The work of Davis, Silverman, and Keller [25] on the survival of spores in a vacuum suggests that

a D-value of 120 hours in an environment with temperatures in excess of 60°C might be reasonable. Thus, the spores brought to the moon and exposed to the vacuum within 30 degrees of the equator should, on the average, suffer a decrease in their population size by a factor of 10^{-1} roughly every lunar day. Once again, it is assumed that such spores are shielded from particle radiation and direct sunlight.

If it were definitely known that all living microorganisms carried to the moon by a spacecraft and dispersed by hard impact are ultimately deposited on the moon's surface, then there would be some justification for the assertion that few organisms—either spores or vegetative cells—survive after 7 or 8 lunar days. If, on the other hand, the opposite situation were known to be the more likely one, namely, that all organisms remained on fragments, what conclusions may be drawn? That fragments might be imbedded at depths of up to 10 or 20 cm has been mentioned earlier. Such fragments (and any organisms attached to them) would achieve a quasi-steady temperature that is possibly quite different from the typical surface temperatures. Knowledge of the lunar temperature distribution over the first few centimeters of crust is based most directly on the moon's apparent temperature as measured at microwave frequencies, and it is known that the results of these measurements represent an average of the temperatures over a depth corresponding roughly to one wavelength [41]. If the microwave temperatures are to be believed (in that they would be representative of the actual temperature that would be attained by a small object buried 1 or 2 cm under the surface), one might expect an organism to experience an essentially constant temperature, generally of the order of -20°C, over the entire lunar day. At -20°C, and in a hard vacuum, vegetative cells might perish at the same rate as they would if deposited on the surface, but spores might remain alive indefinitely. Another uncertainty appears when one realizes that the vacuum at 1 to 2 cm depths—and certainly at even greater depths—need not be as hard as the surface vacuum. It appears that a difference of two orders of magnitude in pressure can make a significant difference in the survivability of an organism. The possibility of the presence of occluded heavy gas, even at depths of a few centimeters, is enough to suggest that an increased pressure—and consequently an increased potential for survival of organisms—may prevail just under the lunar surface.

In short, too little is known of the microclimate at centimeter depths in the surface layers of the moon to draw any safe conclusions about the survivability of microorganisms that may be placed there. Until evidence to the contrary is presented, it should at least be presumed that any spores attached to spacecraft fragments will survive indefinitely.

It should fairly be admitted that the author has not had access to any results of the recent Surveyor VI experiments other than brief descriptions and photographs published in public news media, and these few facts would only seem to indicate that the penetration of high-speed fragments to centimeter depths in the lunar soil is very likely.

Fortunately, of the two modes of microorganism transport posed in Section IV the one that should most often result in subsurface deposition is also the one with the least widespread dispersion pattern. According to the sample calculations, the dispersal of fragments of the impacting spacecraft is limited to distances from the impact site that are one-fifth to one-sixth the "safe" distance obtained from the calculation of the crater debris dispersion pattern. This fact suggests a reasonable procedure that might be followed in predicating the amount of potential contamination to be found near hard impact sites on the moon's surface when the mode of deposition is unknown (as it must be, given our present lack of knowledge of breakup dynamics, adhesion of particles, physical conditions in the lunar soil and survivability of organisms subjected to such conditions). Such a procedure will be described in the conclusions in Section VI.

VI. SOME CONCLUSIONS RELATING TO THE RETRIEVAL OF VIABLE ORGANISMS DEPOSITED ON THE MOON BY UNMANNED LUNAR PROBES

In this final section we will summarize our few major conclusions. Some of the conclusions will be accompanied by explanatory remarks that may help in the interpretation of the conclusions from the point of view of an individual who is attempting to assess the chances of retrieval of viable organisms of terrestrial origin from a sample of lunar soil. There will necessarily be some repetition of material already covered in the previous sections of this report. However, it should not be necessary to emphasize again the fact that our conclusions are derived from only the studies and experimental data that were accessible to us and that seemed correct and relevant to the purposes at hand. Also, the calculations on which many of the conclusions are based have required many assumptions for which justification is weak. For these reasons, we give only rough estimates of numbers (such as ranges, surface densities, characteristic times of microorganism death) even though more exact results would be desirable. Our rough estimates are nevertheless conservative ones by intention.

The major conclusions of this study are:

1. Less than 30 percent of the microorganisms residing on a typical U. S. lunar probe at launch time survived transit to the moon. Thermal kill of organisms during the typical 34- to 80-hour transit times can be neglected.

2. Seven or eight months after touchdown, the contaminated area around the landing point of a typical U. S. unmanned lunar probe making a soft landing on the moon should be confined within a conservative radius of 100 meters.

Remarks: Conclusion 2 is a consequence of the fact that the contamination of the lunar surface by a soft lander is predominantly by the retro-rocket fuel residues and should, therefore, be in the form of surface-deposited organisms which, in view of the material in Section V, should remain in place and suffer an (expected) loss of viability over the stated amount of time. Since there is the chance that small fragments carrying organisms will be dislodged even in a soft landing, there remains the chance that organisms will be deposited below the surface but very near to the landing point. The 100-meter safe radius indicated

in conclusion 2 is a conservative estimate of the maximum range of fragments ejected in a typical soft landing. Little can be said about the contamination around a soft lander prior to the elapse of 7 to 8 months. In the absence of a special study of the deposition patterns of retro-rocket residues, it is urged that within 8 months after touchdown, soft landers be regarded in the same manner as those lunar probes that were known to have made hard impacts. Table VII shows the lunar probes landing or impacting on the moon prior to July 1967; their masses, impact velocities and coordinates (if known); and the breakdown of their bioburden just prior to impact or touchdown (the latter break-down is a repetition of entries in Table III).

3. Organisms remaining on fragments of a typical U. S. lunar probe that has made a hard impact on the moon should be confined almost entirely within a conservative radius of 50 to 60 km about the impact point. It should be presumed that such organisms remain viable for an indefinite period of time.

4. Organisms carried by the crater material formed in the hard impact of a lunar probe may be deposited over the entire surface of the moon. Seven to eight months after impact, however, the contamination of the moon's surface by this class of organisms should be negligible.

5. The distance from the site of hard impact of a typical U. S. lunar probe at which the assumption of uniform deposition of the probe's bioburden over the entire lunar surface becomes a conservative assumption is 240 to 260 km.

Remarks: Conclusions 3, 4, and 5, which are consequences of the material presented in Sections IV and V, suggest a reasonable and safe procedure that might be followed in predicting the chances of retrieval of viable organisms near hard impact sites on the moon. For the sake of simplicity in describing the procedure, it will first be assumed that one wishes to sample the lunar soil at a point on the moon at a time such that all impacts or soft landings of known unmanned craft have occurred within the past 8 months. For such conditions, the procedure would be as follows:

a. If the sampling site is at least 260 km from all impact or landing sites, predict the probability of retrieval on the basis of the assumption that the preimpact bioburdens of all unmanned probes touching the moon up to the sampling time have been uniformly distributed over the surface.

b. If the sampling site lies within 260 km of one or more impact or landing sites, predict the probability of retrieval on the basis of the surface densities of crater ejecta (see Section IV) for each of the impact

TABLE VII

Summary of Hard and Soft Landers as of July 1967
(Information from References 31 and 32)

Lunar Probe	Impact Date	Mass (kg)	Impact Speed	Impact Coordinates	Total Bioburden at Impact*	Estimated Spore Population at Impact*
Luna II	1959 Sept. 13 21h02m23s	390	$>2.38 \frac{km}{sec}$	1°W 30°N	2.9×10^7	1.1×10^7
Ranger IV	1962 April 26 12h50m24s	331	$2.64 \frac{km}{sec}$	130.7°W 15.5°S	2.39×10^7	1.1×10^7
Ranger VI	1964 Feb. 2 09h24m33s	365	$2.64 \frac{km}{sec}$	21.5°E 9.4°N	2.35×10^7	1.1×10^7
Ranger VII	1964 July 31 13h25m49s	366	$2.64 \frac{km}{sec}$	20.7°W 10.7°S	2.28×10^7	1.1×10^7
Ranger VIII	1965 Feb. 20 09h 57m	367	$2.64 \frac{km}{sec}$	24.8°E 2.7°N	2.37×10^7	1.1×10^7
Ranger IX	1965 March 24 14h08m20s	366	$2.64 \frac{km}{sec}$	2.4°W 12.9°S	2.37×10^7	1.1×10^7
Luna V	1965 May 12 19h 10m	1476	$>2.38 \frac{km}{sec}$	8°S 31°S	1.99×10^7	1.1×10^7
Luna VII	1965 Oct. 7 22h08m24s	1506	$>2.38 \frac{km}{sec}$	40°W 9°N	1.94×10^7	1.1×10^7
Luna VIII	1965 Dec. 6 21h51m30s	1552	$>2.38 \frac{km}{sec}$	63.3°W 9.1°N	1.99×10^7	1.1×10^7
Luna IX	1966 Feb. 3 (1:45 EST)	1360	5.5-6.1 m/sec	64.4°W 7.1°N	2.07×10^5	1.1×10^5
Surveyor I	1966 June 2 (1:17:37 EST)	270	3.96 m/sec	43.32°W 2.49°S	1.0×10^5	2.75×10^4
Lunar Orbiter I	1966 ~Oct. 29	387	$2.38 \frac{km}{sec}$	162°E 6.7°N	2.47×10^3	2.47×10^3
Surveyor II	1966 Sept. 23	292	$2.38 \frac{km}{sec}$	?	6.29×10^5	4.95×10^4
Luna XIII	1966 Dec. 24	100	Soft landing	62.1°W 18.9°N	2.06×10^6	1.1×10^6
Surveyor III	1967 April 19	>290	Soft landing	Apollo Zone	1.52×10^6	5.0×10^5

*Taken from Table III

sites within 260 km (the surface densities would be additive) plus the assumption of uniform distribution of the organisms from all other impacts that lie beyond a 260 km radius from the sampling point.

Corrections for the thermally effected die-off of the organisms contributed by each impact site could be made in either (or both) of steps a and b if a slightly sharper estimate were desired, without changing the degree of safety afforded by the procedure.

The procedure in the opposite case—that is, when the sample is taken at any time 8 months or more after the last impact or landing of a lunar probe—is straightforward. If the sampling site lies at least 60 km from the nearest point of a hard impact, then within the general limitations of our calculations one is assured of retrieving at least one viable organism with a probability of 10^{-6} or less. This assurance is independent of the number of probes striking the moon prior to the sampling time and is somewhat independent of the surface area of the sample (though it should by now be obvious that a more careful analysis would be necessary if unreasonably large sample areas, say of total area 100 m^2 or more, were anticipated). If the sampling site lies within 60 km of one or more of the hard impact sites, then the probability of retrieval in this case should be predicted on the basis of the range-of-fragment distributions given in Section V (or, if necessary, adopted from the calculation in Appendix C or from improved versions of it). In this latter case, the overlap of the fragment distribution patterns for all impact sites within 60 km of the sampling area should be taken into account.

The procedures outlined above may be generalized in an obvious way for the intermediate case that occurs when a sample is to be taken near impact sites, some of which have been "born" within 8 months of the time of sample taking, and some of which are older.

APPENDIX A

A JUSTIFICATION FOR THE POISSON DISTRIBUTION

The use of the Poisson distribution for a description of the microbial load on a spacecraft receives some justification when the following model is considered.

Imagine a portion of the surface of a spacecraft to be exposed in a room in which there are airborne microorganisms present. Some of these microorganisms may be deposited on the particular element of surface in the course of time. In turn, organisms so deposited may subsequently be removed by mechanical means, or they may die. The problem is to find the probability that there are precisely a given number of organisms on the element of surface at any given time after the surface element is exposed.

The natural mathematical model for this problem is a "birth and death" process (see Feller [42], Chapter 17, whose notation and development are adopted in this appendix). For brevity, we will hereafter say that the element of surface is in "state" E_i at time t when there are exactly $i \geq 0$ viable microorganisms on the surface at time t. The usual postulates of the birth and death process are assumed; that is, quantities $\lambda_n(t)$ and $\mu_n(t)$ are defined such that

$$\lambda_n(t) + o(h)$$

is the probability that $E_n \rightarrow E_{n+1}$ (one microorganism is added) during the time interval (t, t+h), and

$$\mu_n(t) + o(h)$$

is the probability that $E_n \rightarrow E_{n-1}$ (provided that $n \geq 1$, this is the removal or death of one microorganism) during the time interval (t, t+h). Also, the probability that $E_n \rightarrow E_m$ ($m \neq n+1$ or $n-1$) in (t, t+h) is assumed to be o(h).

The birth and death equations for the desired probability distribution are derived by looking at the mutually exclusive ways in which the microbe population may change in a short time interval (t, t+h), and then letting h tend to zero. Thus, if $P_n(t)$ is the probability that state E_n holds at time t, then

$$P_n(t+h) = P_n(t)\left\{1-\lambda_n(t)h-\mu_n(t)h\right\} + \lambda_{n-1}(t)h\, P_{n-1}(t)+\mu_{n+1}(t)h\, P_{n+1}(t)+o(h);$$

therefore

$$\frac{P_n(t+h)-P_n(t)}{h} = -\left[\lambda_n(t)+\mu_n(t)\right] P_n(t)+\lambda_{n-1}(t)\, P_{n-1}(t)+\mu_{n+1}(t)\, P_{n+1}(t)+\frac{o(h)}{h},$$

and upon taking the limit, $h \to 0$,

$$P_n'(t) = -\left[\lambda_n(t)+\mu_n(t)\right] P_n(t)+\lambda_{n-1}(t)\, P_{n-1}(t)+\mu_{n+1}(t)\, P_{n+1}(t), \qquad (A.1)$$

where

$$\left(' = \frac{d}{dt}\right) \text{ and } n \geq 1.$$

For $n = 0$,

$$P_0'(t) = -\lambda_0(t)\, P_0(t)+\mu_1(t)\, P_1(t)\,. \qquad (A.2)$$

At the time the element of surface is first exposed, say $t = 0$,

$$P_n(0) = p_n, \quad n = 0, 1, 2, \ldots \qquad (A.3)$$

where the p_n's describe some arbitrary distribution satisfying

$$p_n \geq 0, \ \sum_{n=0}^{\infty} p_n = 1\,. \qquad (A.4)$$

Equations (A. 1) through (A. 4) are the mathematical statement of the model. It remains to give some physical meaning to the quantities, λ_n and μ_n, and to analyze the consequences of the mathematical model for certain reasonable choices of these quantities.

A connection between λ_n and μ_n and physical quantities measured in the laboratory can be made by observing their analogy with such quantities as mean free path and mean collision time in gas kinetic theory. Evidently, $\lambda_n(t)$ is the reciprocal of the mean time between consecutive microbe impacts on the particular surface element. It is a function

of many variables among which are the concentration and distribution of airborne microorganisms in the neighborhood of the surface element, the orientation of the surface element with respect to the vertical, and the directions of prevailing air flow. Similarly, $\mu_n(t)$ is the sum of the reciprocals of two mean waiting times, the first being the mean time between consecutive removals of microorganisms from the surface, and the second being the mean waiting time until death for the particular species of microorganisms in question.

If the physical state of the immediate surroundings of the surface element remains substantially constant in time, and if the mean waiting time until death for the microorganisms in question is not age dependent, then it is reasonable to choose

$$\left.\begin{aligned} \lambda_n(t) &= a, \ a > 0, \ \text{constant} \\ \mu_n(t) &= \mu \cdot n, \ \mu > 0, \ \text{constant} \end{aligned}\right\} \tag{A.5}$$

for all $n \geq 0$.

The desired probability distribution is then found by solving the following equations:

$$\left.\begin{aligned} P_n'(t) &= -\left[a+\mu_n\right]P_n(t)+a\,P_{n-1}(t)+\mu[n+1]\,P_{n+1}(t), \ n \geq 1 \\ P_0'(t) &= -a\,P_0(t)+\mu\,P_1(t), \end{aligned}\right\} \tag{A.6}$$

with (A.4) as an initial condition.

Equations (A.6) may be solved to obtain a closed-form expression for the $P_n(t)$. However, some direct consequences of (A.6) are more interesting. For instance, one easily finds that the mean number of viable microorganisms on the surface element at any time t after exposure,

$$M(t) = \sum_{n=1}^{\infty} n\,P_n(t),$$

is given by

$$M(t) = \frac{a}{\mu}\left[1-e^{-\mu t}\right]+M(0)e^{-\mu t} \tag{A.7}$$

(Feller [42], p. 414).

Thus, as $t \to \infty$, $M(t) \to a/\mu$, and exhibits a plateau in microbial population actually observed in some experiments (see McDade, Favero, et al. [8]). More relevant to the purpose of this appendix is the fact that as $t \to \infty$,

$$P_n(t) \to \frac{1}{n!}\left(\frac{a}{\mu}\right)^n e^{-a/\mu} \tag{A.8}$$

independent of the initial distribution given in (A.4). In plain words, this means that the probability distribution for the number of viable organisms on the surface element eventually might be viewed as a Poisson distribution with parameter a/μ.

It is easy to extend these conclusions so that they apply to the entire surface microbial burden of the spacecraft. If there are, say, K surface elements for the entire spacecraft and if each surface element has associated with it values of a_k and μ_k $(1 \leq k \leq K)$, then the probability distribution for the number of viable microorganisms on the surface of the spacecraft becomes a Poisson distribution with the parameter

$$\sum_{k=1}^{K} \left(\frac{a_k}{\mu_k}\right)$$

after the spacecraft has been exposed to a stable environment for a sufficiently long period of time when one assumes each surface has a distribution given by (A.8). The assertion just made follows from the fact that a sum of independent Poisson distributed random variables is itself a Poisson distributed random variable with mean equal to the sum of the means of the individual random variables.

The limitations of the particular birth and death model just presented are apparent when the assumptions that were made are compared with the real conditions that are likely to prevail in a spacecraft assembly facility. First of all, a stable environment is not achieved in any real assembly area; the movement and, indeed, just the presence of human beings preclude this for obvious reasons. Also, the orientations of the spacecraft and its subassemblies are necessarily changed as assembly and checkout proceeds. Secondly, the present model does not incorporate certain important sources of contamination such as human fingers or tools that may touch the spacecraft. Finally, the model assumes airborne clouds of single microorganisms, while experience indicates that most of the airborne contamination is present in the form of clumps of microorganisms or solid

particles on which many microorganisms reside. Though it is believed that most, if not all, of these limitations could in principle be removed by amendments to the model, there is still lacking a firm experimental background which could justify such changes.

APPENDIX B

SOME MICROBIAL DEATH MODELS

1. A Thermal Death Model

Suppose that exactly X microorganisms of the same species and physiological state are exposed to an environment characterized by a known temperature, pressure, humidity, etc. The exposure is begun at, say, $t = 0$ and the effects of this environment upon the growth ability of the microorganisms are observed after a certain amount of time, τ, has passed.

Let T be the random lifetime of an individual organism when subjected to the stated conditions. It is assumed that the lifetimes for the organisms are independent, identically distributed random variables. Thus, let

$$p(\tau) = \text{Prob}\left\{T \geq \tau\right\}$$

be the probability that any one of the microorganisms is viable after a time τ has passed, conditioned upon maintaining the known environmental parameters at their fixed values during that time. It follows that the probability of finding exactly $x(\leq X)$ viable organisms after an exposure of length τ is

$$P(x, \tau | X) = \binom{X}{x} p^x(\tau) [1 - p(\tau)]^{X-x} \qquad \text{(B. 1)}$$

The expected number of survivors after an exposure of length τ is

$$\bar{x}(\tau) = Xp(\tau) . \qquad \text{(B. 2)}$$

In the experimental studies of thermal deactivation of microorganisms, the expected number of survivors, $\bar{x}(\tau)$, is usually estimated from colony counts of samples removed from the environment at several times throughout the duration of the exposure. The data in these studies is usually presented as a table or graph of $\log_{10}\bar{x}(\tau)$ versus elapsed time τ.

As can be illustrated by the results of many different investigators, the graph for this function is invariably nondecreasing but may be a straight line of negative slope, a concave or convex curve, or a combination of these patched together over nonoverlapping τ intervals. Indeed, there appears to be a considerable controversy over the issue of the nonlinearities that appear in survival curves (see, for instance the review by Schmidt [43]) through which the writer of this report does not feel that he is competent to find a pathway.

Instead, the practice currently employed in engineering studies of spacecraft sterilization will also be employed in the present study. In its essentials, this practice is to fit the best straight line of negative slope to the data representing the graph of $\log_{10} \bar{x}(\tau)$ over the region of interest. Thus, the survivor curve may be given approximately by

$$\log_{10} \bar{x}(\tau) = \log_{10} X - K\tau, \quad 0 \leq \tau, \tag{B. 3}$$

which is tantamount to making the assumption that the random lifetimes of the individual microorganisms are exponentially distributed. Writing (B. 3) as

$$\log_{10} [x(\tau)/X] = -\frac{\tau}{D} , \tag{B. 4}$$

one sees that $D = 1/K$ is the exposure time required to reduce the survivors by one-tenth.

The magnitude of the error incurred in making the approximation (B. 3) depends, of course, upon the range of the exposure time over which the approximation is forced to apply. For most cases, it would appear that the error is largest either for very short exposures or for the very long exposures which result in a number of survivors that is much less than the initial population size. In any case, when one considers the magnitude of the uncertainties present in other parameters appearing in the present work, the uncertainty contributed by the use of such a logarithmic death model becomes unimportant.

2. Radiation Death Models

For most species of bacteria and under a fairly wide range of auxiliary conditions, it is possible to assume an exponential decrease of the microbial population under irradiation by ultraviolet light of wavelengths near 2650 Å [29]. Thus, a formula similar to (B. 4) can be written:

$$\log_{10}\left[N(R)/N_o\right] = -\frac{R}{R_{10}} \qquad \text{(B.5)}$$

where N(R) is the expected number of survivors from an initial population of N_o organisms after dosage by R ergs/cm^2 of ultraviolet light of wavelengths near 2650 Å. R_{10} is the dosage in ergs/cm^2 required to reduce the survivors by one-tenth; it depends upon the species and physiological state of the organisms under irradiation and also upon the auxiliary variables (temperature, pressure, humidity, etc.) characterizing the environment. It should be emphasized that (B.5), like the formula (B.4) adopted for a thermal death model, is an "engineering" approximation to the truth of the matter. The same reservations and limitations mentioned for the probability of thermal kill are intended to apply to the probability of kill by ultraviolet radiation.

For ionizing radiations (radiations which are capable of producing ion-electron pairs in the irradiated material) things are much more uncertain. In considering the effects of ionizing radiations on terrestrial microorganisms deposited on the lunar surface, Sagan [30] assumes an exponential survival law and gives the following formula for the number of survivors, N of an initial population, N_o, after exposure to ionizing radiation of intensity I ergs/cm^2-sec for t seconds:

$$\log_{10}(N/N_o) = -\frac{\left[1 - e^{-(\mu/\rho)\rho a}\right]}{214\,\rho a}\,\frac{It}{D}\,. \qquad \text{(B.6)}$$

In the above formula, D is the mean lethal dose of a given radiation for the particular organism being irradiated (D is measured in reps, and 1 rep = 0.93 rad in average biological tissue), μ/ρ is the mass absorption coefficient of the organism in cm^2/gm, ρ is the organisms's density in gm/cm^3, and "a" is the characteristic diameter of the organism in cm. It is easy to see the physical meaning of (B.6), when written in the following form:

$$N = N_o \exp\left\{-\frac{\left[1 - e^{-(\mu/\rho)\rho a}\right]}{93\,\rho a}\,\frac{It}{D}\right\} \qquad \text{(B.6')}$$

The factor, $It/93\,\rho a$, in the exponent is the dose in reps <u>delivered</u> to a single cell up to time $t \geq 0$, and the other factor in the exponent, $[1 - \exp\{-(\mu/\rho)\rho a\}]$ is essentially the fraction of the delivered dose that is absorbed by the cell. The expression (B.6'), for the number of survivors presumes, of course, that the organisms have independently distributed lifetimes.

Table B.I, columns 4 and 5, gives the time, t_{10}, required to reduce the number of microorganisms by one-tenth when the population is exposed (with no shielding) to fluxes of energetic protons from the several sources available between the earth and the moon. (The Van Allen belt radiations are not considered for the reason that they are likely to have a negligible effect: the times of possible exposure, 10 hours or less, are short and it is very likely that the lunar probes are well shielded by their protective cannisters during passage through the potentially lethal parts of the belts.) Sagan's formula, (B.6), has been used to compute these characteristic times with $D = 10^7$ rep, $a = 10^{-4}$ or 10^{-6} cm, and $\rho = 1$ gm/cm^3. The absorption coefficient μ/ρ has been roughly estimated by

$$\mu/\rho \cong \frac{1}{E}\left(-\frac{dE}{d\xi}\right)_{ion} ,$$

where E is the particle energy and $(-dE/d\xi)_{ion}$ is the ionization loss per unit of absorber in the cell material. The ionization loss is found by the well-known formula [44]:

$$\left(-\frac{dE}{d\xi}\right)_{ion} = \frac{4\pi Z^2 e^4}{mV^2}\frac{n}{\rho}\left[\ln\frac{2mV^2}{\bar{I}(1-\beta^2)} - \beta^2\right]\frac{\text{ergs-cm}^2}{\text{gm}} .$$

For protons, $Z = 1$, $e = 4.80 \times 10^{-10}$ e.s.u., and assuming that biological tissue is mostly water,

$\bar{I}$ (the average ionization potential) = 80 eV ,

and $\frac{n}{\rho}$ (the No. of electrons/gm) $\cong 3 \times 10^{23}$.

The value, $a = 10^{-4}$ cm, corresponds to a typical spore characteristic diameter while $a = 10^{-6}$ cm might be the characteristic size of a site in the cell in which the energy must be deposited before deactivation of the cell can occur. It is felt that these values represent the end points of the range of what might be the size of the sensitive area in a cell.

TABLE B.I

Irradiation Times, t_{10}, Required to Reduce Microbial Population by One Decade with Proton Fluxes from Various Sources

Source	Energy	Average Intensity ($ergs/cm^2\text{-}sec$)	t_{10} (sec)	
			If $a = 10^{-4}$ cm	If $a = 10^{-6}$ cm
Solar Wind				
Inside magnetosphere	100 eV	1.64×10^{-6}	1.3×10^{11}	1.3×10^{9}
Outside magnetosphere	1 keV	80	2700	31
Cosmic Rays	20 MeV	1.3×10^{-7}	1.6×10^{19}	1.6×10^{19}
Solar Flares				
(Low-energy)	100 MeV	2.3×10^{-4}	1.4×10^{17}	1.4×10^{17}

The mean lethal dose, $D = 10^7$ reps, is probably conservative (too high) by a factor of 10 for spores and perhaps 100 for vegetative cells [45]. The characteristic times, t_{10}, given in Table B.I would be reduced by these factors if the lower D-values are to be taken.

As was mentioned earlier, there are many uncertainties involved in the use of (B.6) to predict the number of survivors after a given dose of ionizing radiation. For one thing, it is known that the random lifetimes of certain organisms in the presence of ionizing radiation are not exponentially distributed. Also, it is known that the fraction of the survivors among certain organisms exposed to ionizing radiation is not always an increasing function of the linear energy transfer (roughly, the energy deposition per unit path length in biological material), given equal amounts of deposited energy [45]. Nevertheless, the characteristic times computed from (B.6) and the other assumptions very likely show the correct relative effects of protons of various energies. The low energy solar wind protons lose energy rapidly, even in very thin layers of biological material. For this same reason, a small amount of material covering the cells will be sufficient to protect them from the solar wind protons. On the other hand, the flux of high energy protons, such as from the cosmic ray and solar flare sources, are too small to have appreciable effect even though these radiations may penetrate significant amounts of shielding material.

APPENDIX C

A RANGE DISTRIBUTION FOR FRAGMENTS OF A SPACECRAFT MAKING A HARD IMPACT ON THE MOON

1. The Velocity Distribution of Fragments

Suppose that a spacecraft impacts upon the moon and, just upon impact, breaks into N_f fragments. Let E_i be the kinetic energy of the craft just before impact, and let E_f be the amount of kinetic energy given over to fragment kinetic energy after the impact.

Let an individual fragment have mass M and kinetic energy E. If such a fragment is to be chosen at random from among the N_f fragments formed in the impact, then prior to making a choice, M and E must be regarded as random variables with some distribution:

$$F(m, e) = \Pr\left\{M \leq m,\ E \leq e\right\} .$$

Now, the conservation of energy requires that $0 \leq E \leq E_f$ and intuition suggests that $m_o \leq M \leq M_s$, where m_o is some small mass, and M_s is the mass of the impacting spacecraft. Thus, the distribution F(m, e) vanishes outside of the set:

$$D = \left\{(m, e) \mid m_o \leq m \leq M_s,\ 0 \leq e \leq E_f\right\} .$$

It is also physically reasonable to assume that F(m, e) has a continuous density;

$$f(m, e) = \frac{\partial^2 F(m, e)}{\partial m \partial e} ,$$

so that f(m, e)dm de can be interpreted in the usual way as the probability of finding a fragment with mass m to m + dm and kinetic energy e to e + de.

It follows that

$$\int_D f(m, e)\,dm\,de = 1 \qquad \text{(C. 1)}$$

$$\int_D mf(m, e)dm\ de = \bar{m}, \tag{C. 2}$$

where $\bar{m}$ is the expected mass of a fragment. Also,

$$\int_D ef(m, e)dm\ de = \bar{e}, \text{ and} \tag{C. 3}$$

$$\int_D \sqrt{\frac{2e}{m}}\, f(m, e)dm\ de = \bar{v}, \tag{C. 4}$$

where $\bar{e}$ is the expected kinetic energy of a fragment and $\bar{v}$ is the expected fragment speed.

Now suppose that $\bar{e}$ and $\bar{m}$ are known for a given set of impact conditions. Is it possible to construct f(m, e) with only these quantities at hand? The answer is obviously no, because first moments alone do not in general uniquely determine a distribution. However, there are several consistent ways of deriving distributions which have a given set of moments, and perhaps the most physically meaningful one of these is the so-called "Maximum Entropy Principle." The method is best illustrated by applying it to the problem at hand. Some justification for such an application will follow.

To begin, a consistent measure of uncertainty associated with any distribution of fragment mass and energy satisfying (C. 1) through (C.3) is defined. This measure of uncertainty which, in statistical mechanics, would be proportional to the physical entropy of a system, is here given by

$$S_f = -\int_D f(m, e) \ln [f(m, e)]\, dm\ de. \tag{C. 5}$$

The application of the principle consists of finding the unique distribution that maximizes S_f subject to the constraints (C. 1) through (C.3). This program is accomplished in the usual way by introducing Lagrange multipliers, $\lambda_0 + 1$, λ_1, λ_2, and forming the quantity.

$$S_f' = -\int_D f(m, e) \ln [f(m, e)]\, dm\ de + (\lambda_0 + 1) \int_D f(m, e)\, dm\ de$$

$$+ \lambda_1 \int_D e\, f(m, e)\, dm\ de + \lambda_2 \int_D mf(m, e)\, dm\ de.$$

Then, one requires that

$$\delta S_f' = \int_D \left\{ -\ln[f(m, e)] - 1 + (\lambda_0 + 1) + \lambda_1 e + \lambda_2 m \right\} \delta f(m, e) dm\, de = 0$$

and since $\delta f(m, e)$ may now be arbitrary (the constraints being taken into account by the introduction of the new variables λ_0, λ_1, λ_2), it follows that

$$-\ln [f(m, e)] + \lambda_0 + \lambda_1 e + \lambda_2 m = 0,$$

or

$$f(m, e) = \exp [-\lambda_0 - \lambda_1 e - \lambda_2 m]. \tag{C. 6}$$

Equations (C. 1) through (C. 3) may now be used in conjunction with (C. 6) to find λ_0, λ_1, λ_2 in terms of the given parameters. When this is done, one finds:

$$e^{-\lambda_0} = \lambda_1 \lambda_2 \left[1 - e^{-\lambda_1 E_f}\right]^{-1} \cdot \left[e^{-\lambda_2 m_o} - e^{-\lambda_2 M}\right]^{-1}, \tag{C. 7}$$

$$\bar{e} = \frac{1}{\lambda_1} - \frac{E_f e^{-\lambda_1 E_f}}{\left[1 - e^{-\lambda_1 E_f}\right]}, \tag{C. 8}$$

$$\bar{m} = \frac{1}{\lambda_2} + \frac{\left[m_o e^{-\lambda_2 m_o} - M e^{-\lambda_2 M}\right]}{\left[e^{-\lambda_2 m_o} - e^{-\lambda_2 M}\right]}. \tag{C. 9}$$

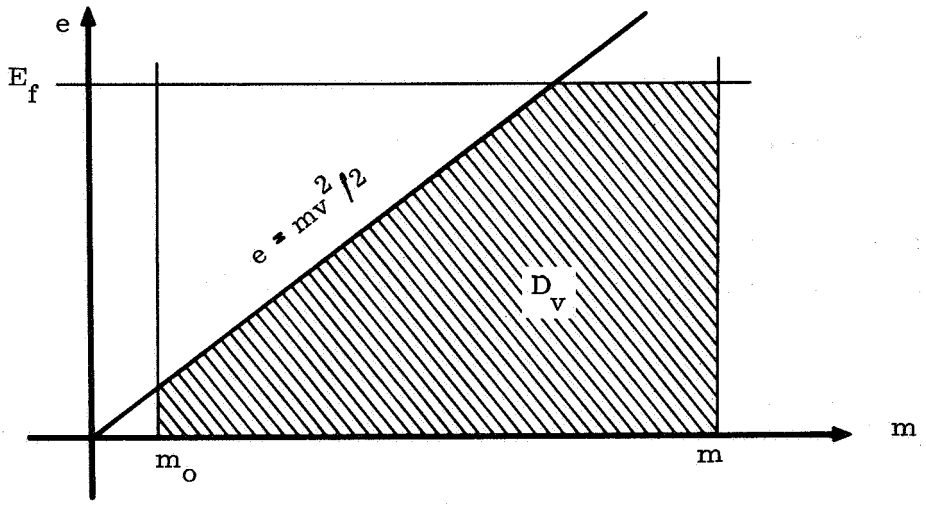
Equations (C. 8) and (C. 9) are transcendental equations in λ_1 and λ_2 and may be solved in terms of the known quantities (E_f, m_o, M, $\bar{e}$, and $\bar{m}$). Then (C. 7) may be used to find the normalizing term, $e^{-\lambda_0}$.

One sees that the application of the "Maximum Entropy Principle" to the problem leads to a truncated exponential distribution of fragment mass and kinetic energy in which the size and kinetic energy are independent random variables. The distribution (C. 6) may now be

used to find the speed distribution of the fragments. The speed is $v = \sqrt{2e/m}$ for a particle of mass m and kinetic energy e. Thus, for any $v > 0$, let S_v be the set

$$S_v = \left\{(m, e) \,\middle|\, \sqrt{2e/m} \leq v,\ e \geq 0,\ m > 0\right\}$$

and let $D_v = S_v \cap D$ where D is the support set given earlier. D_v is the shaded region shown in the diagram below:



If V is the speed of a fragment to be chosen at random, then the distribution of speeds is:

$$G(v) = \Pr\left\{V \leq v\right\} = \int_{D_v} f(m, e)\, dm\, de$$

$$= \epsilon^{-\lambda_0} \int_{m_o}^{M} \epsilon^{-\lambda_2 m} \left\{ \int_0^{\min\left[E_f, \frac{mv^2}{2}\right]} \epsilon^{-\lambda_1 e}\, de \right\} dm, \qquad \text{(C. 10)}$$

(where ϵ is here used to denote the base of the natural logarithm, i.e., $\epsilon^{-x} = \exp(-x)$). The integration of (C.10) gives

$$G(v) = \begin{cases} 0 \quad \text{if } v < 0, \\ \dfrac{\epsilon^{-\lambda_0}}{\lambda_1\lambda_2}\left[\epsilon^{-\lambda_2 m_o} - \epsilon^{-\lambda_2 M}\right] - \dfrac{\epsilon^{-\lambda_0}}{\lambda_1 p(v)}\left[\epsilon^{-m_o p(v)} - \epsilon^{-Mp(v)}\right], \\ \qquad\qquad \text{if } 0 \le v \le \sqrt{2E_f/M}\ , \\ \dfrac{\epsilon^{-\lambda_0}}{\lambda_1\lambda_2}\left[\epsilon^{-\lambda_2 m_o} - \epsilon^{-\lambda_2 M}\right] - \dfrac{\epsilon^{-\lambda_0}}{\lambda_1 p(v)}\left[\epsilon^{-m_o p(v)} - \exp\left(-\dfrac{2E_f}{v^2}\, p(v)\right)\right] \\ -\dfrac{\epsilon^{-\lambda_0}}{\lambda_1\lambda_2}\epsilon^{-\lambda_1 E_f}\left[\exp\left(-\dfrac{2\lambda_2 E_f}{v^2}\right) - \epsilon^{-\lambda_2 M}\right], \\ \qquad\qquad \text{if } \sqrt{2E_f/M} \le v \le \sqrt{2E_f/m_o}\ , \\ 1, \text{ if } v > \sqrt{2E_f/m_o}, \end{cases} \tag{C.11}$$

where $p(v) = \lambda_2 + \dfrac{\lambda_1}{2} v^2$.

The expected fragment speed is most easily obtained from (C.4). The result is

$$\bar{v} = \sqrt{2}\, \epsilon^{-\lambda_0} \lambda_1^{-3/2} \lambda_2^{-1/2} \cdot \gamma(3/2, \lambda_1 E_f)[\gamma(1/2, \lambda_2 M) - \gamma(1/2, \lambda_2 m_o)] \tag{C.12}$$

where $\gamma(a, x) = \displaystyle\int_0^x e^{-t}\, t^{a-1}\, dt$.

Before proceeding to discuss the justification for the speed distribution, (C. 11), that has just been derived, it might be helpful to consider a sample case to which it might be applied.

Consider an impact for which

$$M = 365 \text{ kg} = 3.65 \times 10^5 \text{ gm}$$

$$V_i \text{ (impact speed)} = 2.6 \text{ km/sec} = 2.6 \times 10^5 \text{ cm/sec.}$$

The kinetic energy of the projectile just before impact, $1/2\ MV_i^2$, is then 1.23×10^{16} ergs, and it will be assumed that about 0.01 percent of this energy is given over to the total kinetic energy of the fragments formed during the breakup of the projectile upon impact (see Reference 46 for some justification). Thus, $E_f \cong 1.23 \times 10^{12}$ ergs. Assuming that $N_f \cong 10^5$ (which is something like the total number of piece parts in an unmanned lunar probe), one finds that

$$\bar{e} \cong \frac{E_f}{N_f} = 1.23 \times 10^7 \text{ ergs}$$

$$\bar{m} \cong \frac{M}{N_f} = 3.65 \text{ gm} .$$

Next, note that for $N_f \gg 1$ and $m_o \ll M$, the Equations (C. 8) and (C. 9) are solved by

$$\lambda_1 \cong 1/(\bar{e}),\ \lambda_2 \cong 1/(\bar{m})$$

to a very good approximation, and under these same conditions ($N_f \gg 1$, $m_o \ll M$), the expected fragment speed, $\bar{v}$, is well approximated by $(\pi/2)(2\bar{e}/\bar{m})^{1/2}$ which, with the present sample values, gives $\bar{v} = 4 \times 10^3$ cm/sec or 40 m/sec — a seemingly reasonable speed. The maximum range of a fragment ejected at this average speed on the moon's surface would be about 1 km.

Justification for the application of the Maximum Entropy Principle should come ideally from agreement with empirical evidence and, unfortunately, no such evidence can be offered here. However, it is worthwhile to point out the similarities of the distribution of fragment

mass and energy with results from studies of phenomena similar to impact fragmentation. The wartime studies of the mass and size distribution of case fragments formed in the explosion of bombs, shells, and grenades yielded, for instance, an approximate mass distribution of the form [47]

$$N(>m) = A\,\epsilon^{-(m/\mu)^n},$$

where N(>m) is the number of fragments with masses greater than m, μ is a measure of the coarseness of fragmentation, and A and n are constants; and where n = 1/2 for thin-walled shells and n = 1/3 for thick-walled shells, or the so-called three-dimensional breakup. The similarity of this mass distribution with the cumulative mass distribution obtained from (C.6) is evident, though the physical meaning of an n = 1 is not clear. Of course, there need not always be a strong similarity between the processes of case fragmentation in the explosion of gun shells and the fragmentation of an object of complex structure upon impacting a surface at high velocities. It is easy to imagine circumstances in which the mass distribution of the fragments of an impacting projectile is more nearly reflected by the cumulative mass distribution of all component parts of the projectile. (In other words, fracturing at impact could occur mainly at the joints between the piece parts.) Indeed, impacts of aircraft or rockets into sand or lightly compacted alluvium, at speeds of a few hundred meters per second, do seem to give such a mass spectrum as an inspection of the debris surrounding the impact craters in such events will show. The components and structural members of the projectile are not usually shattered but are separated from one another along joints which, presumably, have the lowest tensile strength.

At impact speeds of several kilometers per second, there is some scant evidence to show that considerable shattering does occur. In one case mentioned to the author by Mr. Clifford Long of Sandia Laboratories, a Nike Tomahawk rocket motor and case impacted a dry lake bed at Tonopah, Nevada, with a speed of about 6200 ft/sec (or 1.88 km/sec). According to a witness of the event, the results of the impact were much like an explosion: a cloud of crater debris immediately formed through which vehicle fragments emerged. These fragments were dispersed out to about 100 yards from the impact point and few of them had a characteristic size larger than a centimeter. The impact crater contained some larger fragments and was approximately 5 feet deep and 15 feet in diameter.

Of the information made available to the author on the impacts of complex objects at high velocities, the particular event mentioned above comes the nearest to reproducing the conditions of hard impact of a lunar probe upon the moon. But such information has been found to be crude for the purposes of this study since the impacts that have been observed are either accidental or have been arranged for the study of other phenomena such as impact cratering in different materials. At best, one may expect to get only rough estimates of the degree of fragmentation and the dispersal of the fragments from these events. In turn, from such estimates, it is then possible to gain some idea of total fragment number and that portion of energy given over to fragment kinetic energy—quantities which can be used to obtain a "first approximation" to the velocity distribution of the fragments by means of the Maximum Entropy Principle. On the other hand, if and when the results of more thoroughly documented studies of fragmentation of complex projectiles are made available, the more standard techniques of statistics and the physics of the problem may be used to deduce a velocity distribution in a more satisfying way.

Even in the approach to finding a velocity distribution that has been taken here, the fragment number, N_f, and the total fragment kinetic energy, E_f, should ideally be themselves regarded as random variables and be treated accordingly. However, it was decided to choose values for these quantities that were at the same time obviously conservative and yet justifiable in terms of simple conservation of energy and mass and the facts presented by the few observations of relevant impact events.

2. The Range Distribution of Fragments

Consider the ejection of a fragment of mass m from a point 0 on the moon's surface (see Figure C. 1).

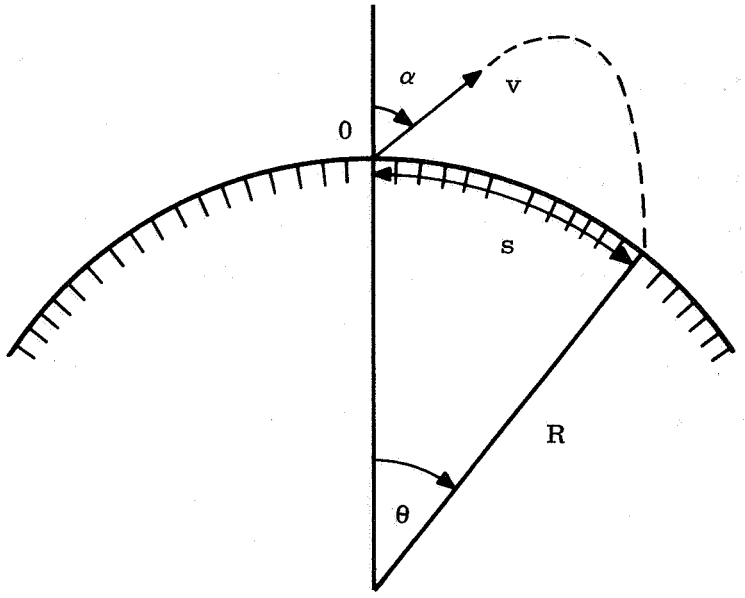


Figure C. 1

The fragment has an initial speed v and is ejected at an angle α measured from the local vertical direction at 0. Assuming a perfectly spherical moon of radius R(=1738 km) and a surface gravity g(=162 cm/sec^2), it is found that the angular range, θ, from the point of ejection to the point of impact of the particle is given by (see, for instance, Reference 48:

$$\theta = \pi - 2 \tan^{-1}\left(\frac{\cos 2\alpha + \rho^{-1} - 1}{\sin 2\alpha}\right) \qquad \text{(C. 13)}$$

where $$\rho = \frac{v^2}{2gR} = \frac{v^2}{v_e^2}, \text{ and}$$

v_e is the moon's escape velocity (about 2.38 km/sec). Note that any fragment with a speed not less than v_e and an ejection angle $\alpha \leq \pi/2$ will be lost to the gravitational field of the moon.

The linear distance along the moon's surface between the point of ejection and the point of impact, s, is just $R\theta$, with θ given by (C. 13).

The results of Part 1 of this appendix (granting their acceptability) may now be used in conjunction with the range formula, (C. 13), to find a range distribution of the fragments resulting from the breakup of a lunar probe upon hard impact on the moon's surface. Because of a general lack of knowledge about the breakup dynamics, it is necessary to make two additional assumptions. These assumptions are (1) fragments are ejected isotropically on the lunar surface from an imaginary point whose lunar coordinates are those of the lunar probe's nominal impact point, (2) the angle of ejection of a fragment is independent of the fragment mass and speed.

It is believed that assumptions (1) and (2) lead to a fragment range distribution that is somewhat conservative in the sense that it predicts the dispersal of fragments over an area larger than that which would be observed in an actual impact under identical conditions. In real impacts, it is possible that extensive fracturing of the projectile, if it occurs at all, occurs after the projectile has penetrated the target and the crater has begun to form. Thus, trajectories of some of the fragments starting with ejection angles no greater than $\pi/2$ would be terminated in the nearby crater walls.

Let S be the range measured along the surface of the moon of a randomly selected particle formed in an impact, and let the distribution of S be

$$P(s) = \Pr\left\{S \leq s\right\}.$$

In order to construct a formula for P(s) that is suitable for numerical computation, note that for a given speed of ejection, v, not exceeding $v_e/\sqrt{2}$, there is an ejection angle such that the range, s, will be a maximum, and ejection at any other angle will cause the fragment to have a secondary impact point at a distance along the moon's surface from the impact point that is less than s. The angle corresponding to the maximum range for a given ejection speed, v, not exceeding $v_e/\sqrt{2}$, is found by setting the partial derivative of $R\theta$ [where θ is given by (C. 13)] with respect to α equal to zero. Once the angle corresponding to the maximum range has been found, it may be substituted for α in (C. 13) to give an expression for the maximum range as a function of the ejection velocity which, in turn, may be inverted to express ejection velocity as a function of maximum range. After carrying out this procedure, it is found that

$$v(s) = \frac{v_e}{\cos(s/2R)} \left[\sin(s/2R) - \sin^2(s/2R)\right]^{1/2} \qquad \text{(C. 14)}$$

where R = 1738 km is the moon's mean radius.

Now since it has been assumed that all ejection angles are equally probable, it is seen that

$$P(s) = \Pr\left\{S \leq s\right\} = \Pr\left\{V \leq v(s)\right\} = G[v(s)], \qquad \text{(C. 15)}$$

where G(v) is the velocity distribution (C. 11).

For chosen values of s, (C. 14) and (C. 11) may be used to compute P(s). The examples provided in Section IV (Figures 1 through 3, and Table V) were obtained by a numerical calculation that employs just this procedure.

APPENDIX D

EJECTION OF LUNAR SOIL BY A SPACECRAFT MAKING A HARD IMPACT ON THE MOON

1. An Acknowledgment

The calculations of dispersal of crater material to be presented in this appendix are largely based upon Reference 49, a report by D. E. Gault, E. M. Shoemaker, and H. J. Moore concerning the dispersal of lunar material by meteoroid impact. Since it is appropriate that a clear distinction be made between the ideas and data presented by these authors in their report and the extrapolations of their ideas to be made in the present appendix, it will therefore be convenient to simply refer to "GS&M" when necessary and to drop the usual means of designating references when referring only to these authors.

2. The Mass Excavated in the Impact

Observations of the amount of material excavated in shallowly buried explosions or by hypervelocity impact upon thick targets seem to indicate that the excavated mass is proportional to a power of the expended energy. In the case of impact, if M_e is the excavated mass, then

$$M_e = k_1\left(\frac{1}{2} M V_i^2\right)^{\alpha}, \tag{D.1}$$

where $(1/2)M V_i^2$ is the kinetic energy of the projectile, and k_1 and $\alpha (> 0)$ are constants. For the impact of aluminum spheres on solid basalt targets, GS&M set $\alpha = 1$ but use a conservative value for k_1; namely, $1/k_1 = 8 \times 10^8$ erg/gm. For impacts in unconsolidated materials, it appears that the excavated mass is at least three times the amount excavated in consolidated basalt under identical impact conditions. In calculating the mass carved out of the lunar surface by the hard impact of a spacecraft, it is, therefore, justifiable to retain the first power dependence upon kinetic energy suggested by GS&M, and set

$$k_1 = \left(\frac{3}{8 \times 10^8}\right) \text{ gm/erg} . \tag{D-2}$$

For these values, (D.1) gives an ejected mass of 4.62×10^7 gm for the impact of a 365 kg spacecraft upon the moon at a speed of 2.6 km/sec. If one then assumes that the lunar soil is largely unconsolidated to depths of a few meters and has a mean density of about 1.2 gm/cm^3 [50], one finds that a hemispherical crater formed by the ejection of such a mass would have a diameter of 5.2 meters, or 17 feet. Grolier and Schenk [51] have tentatively identified the Ranger VIII impact crater on photographs made from Lunar Orbiter II; the crater so identified has a diameter of about 7 meters and a calculated depth of 1.59 meters. On the basis of the density of the lunar soil postulated above, and the assumption that the suspected Ranger VIII crater is a spherical segment, we find that the ejected mass must have been about 3.9×10^7 gm. Given the many uncertainties concerning the physical nature of the lunar crust and the impact dynamics, the order-of-magnitude agreement between the ejected mass computed on the basis of (D.2) for Ranger VIII and the ejected mass obtained from the observed dimensions of the most likely crater is encouraging.

3. The Dispersal of the Excavated Mass

The ejection of mass from the crater formed at impact is not necessarily isotropic. For the hypervelocity impact of aluminum spheres on hard basalt targets, GS&M have observed that the ejection angle of the debris is definitely related to the speed of ejection. In their report, an experimentally derived curve of ejection angle versus the logarithm of the ejection speed is presented for an impact on hard basalt. They also discuss the shape of the ejection angle versus ejection speed curve when the impact occurs on targets of low bearing strength (although no specific data is presented). From the substance of their remarks, one is lead to expect that in target material of low strength, the ejection angle versus ejection speed relation looks something like that shown in Figure D.1.

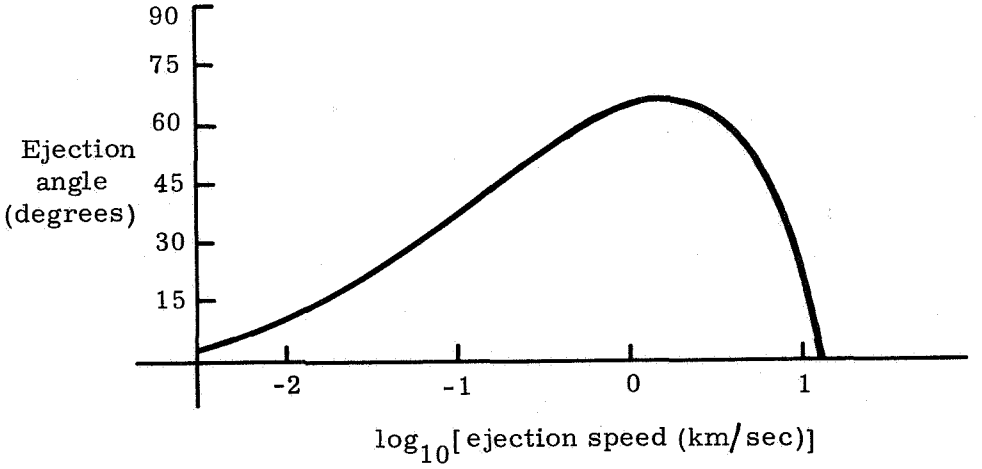


Figure D.1

In Figure D.1, the ejection angle is measured from the horizontal direction and, of course, azimuthal symmetry of the ejection pattern is assumed. The mass ejected at highest speeds comes off at low angles (the "jetting" effect which probably occurs just after contact between projectile and target). For consecutively lower speeds, the ejection angle increases, passes through a maximum the value of which is probably dependent on the initial projectile shape and the subsequent mode of deformation, and then declines to small angles again for the lowest speeds.

The general shape of the curve given in Figure D.1 is based on evidence from small-scale impact experiments, and there is little theory to suggest ways in which such results might be effectively scaled so that applications to large-scale impacts of complex projectiles with rather large impact energies could be made. Nevertheless, an attempt has been made here to perform the scaling for the purpose of computing the dispersal of the lunar soil that occurs when a spacecraft of mass 300-1000 kg makes an impact on the moon at velocities of the order of 3 km/sec. The way this has been done is shown in Figure D.2.

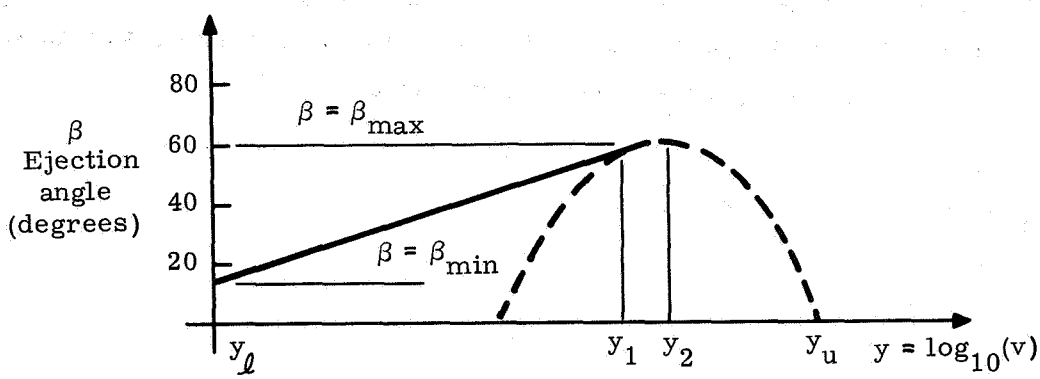


Figure D.2

Since only the general shape of the curve is known, some liberties have been taken in choosing an analytic form. A parabola has been chosen for the high-velocity part of the curve (between $y = y_1$ and $y = y_u$) while the low-velocity portion is approximated by a straight line (between $y = y_\ell$ and $y = y_1$).

Thus,

$$\beta = \begin{cases} \beta_{max} - a_2(y - y_2)^2 & y_1 < y \leqq y_u \\ \beta_{min} + a_3(y - y_\ell) & y_\ell \leqq y \leqq y_1 \end{cases} \qquad \text{(D.3)}$$

It is assumed that β_{max}, β_{min}, y_u, y_ℓ, y_2 can be scaled or determined directly from the physical quantities characterizing the impact. The parameters a_2, a_3, and y_1 are then determined by the requirement that the straight line join smoothly to the parabola (i.e., the curves and their first derivatives match at $y = y_1$).

In reality, β_{max} and β_{min} are probably dependent upon the projectile shape and its mode of breakup upon impact. Therefore, these variables have been treated as free parameters for the time being. The minimum angle of ejection is likely to be no less than 10 degrees, while the results of GS&M for aluminum spheres on <u>hard</u> basalt targets show $\beta_{max} \simeq 60°$ at impact speeds of 6.1 to 6.4 km/sec. The logarithm of the maximum velocity of ejection, y_u, is scaled by applying a formula suggested by GS&M. At impact speeds of about 6.3 km/sec (aluminum spheres on hard basalt), the maximum ejection speed observed was about 20 km/sec. At a different impact speed V_i,

$$y_u = \log_{10}(v_{max}), \quad \text{where} \qquad \text{(D-4)}$$

$$v_{max} = \left(\frac{V_i}{6.3}\right) 20 \text{ (km/sec)} \ .$$

There is no scaling law for the speed corresponding to the maximum ejection angle but the results of GS&M suggest that this speed is of the order of the projectile impact speed, V_i. Thus, it seems reasonable to assume that

$$y_2 = \log_{10}(V_i), \quad V_i \text{ in km/sec} \ . \qquad \text{(D-5)}$$

The choice of a lower limit on the velocity of ejection is clearly arbitrary and it makes no sense to consider speeds much less than 10 meters/sec. Thus, it is assumed that

$$y_\ell = \log_{10}(10^{-2}) = -2 \ . \qquad \text{(D. 6)}$$

Equation (D. 3) in conjunction with (D. 4) through (D. 6) provides a relation between ejection angle and the speed of ejection. However, it is also necessary that the amount of mass ejected at a given speed be known before one can find the way that the total mass excavated by the impact is spread over the surface of the moon. Again, the most relevant data is found in GS&M. For aluminum spheres on hard basalt (impact speeds of 6.1 to 6.4 km/sec), their cumulative mass versus ejection velocity distribution for crater ejecta looks something like that shown in Figure D. 3.

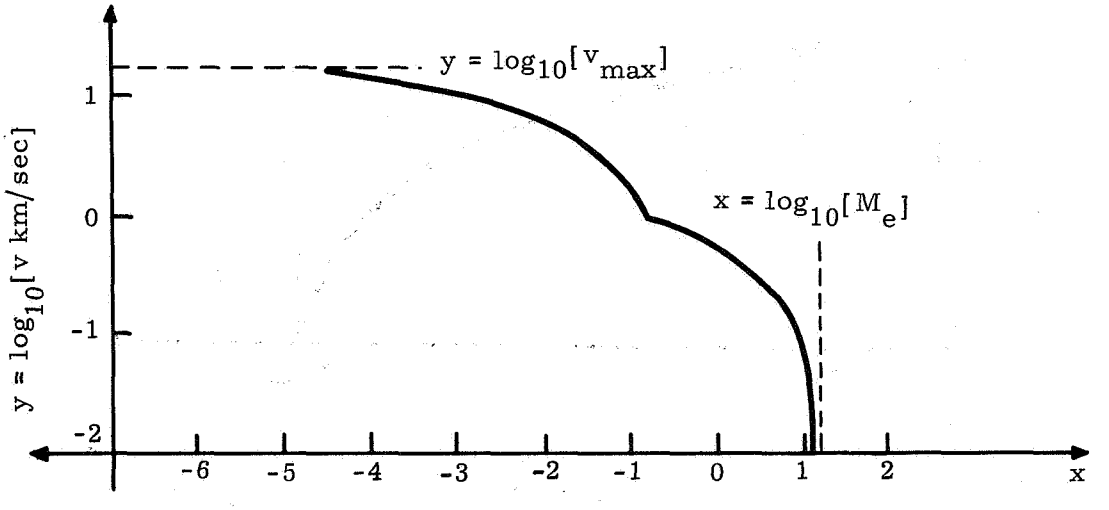


Figure D. 3

Figure D. 3 shows x, the logarithm of the cumulative mass in grams ejected from the crater at speeds greater than v, as a function of y, the logarithm of the ejection velocity measured in units of km/sec. The upper end of the curve (as x increases) is limited by the logarithm of the total excavated mass, M_e, while the lower end of the curve (x decreasing) is limited by the logarithm of the maximum ejection speed, v_{max}. The "shoulder"

in the curve near the coordinates (x = -1, y = 0) is believed by GS&M to be associated with a transition from plastic to elastic flow behind the shock front propagating into the target material from the point of impact.

GS&M say nothing about the applicability of the cumulative mass versus velocity distribution (shown in Figure D.3) to impacts in unconsolidated material such as sand or alluvium. They do suggest some scaling formulae for different impact speeds and energies, however. Thus, for the purpose of the problem which is the concern of the present appendix, it has been assumed that the curve shown in Figure D.3 (or something very like it) is relevant. Figure D.4 shows the scheme by which we have attempted to adopt the data of GS&M to our purposes. Again, some liberties have been taken in choosing an analytic form since details of the curve are not firmly known.

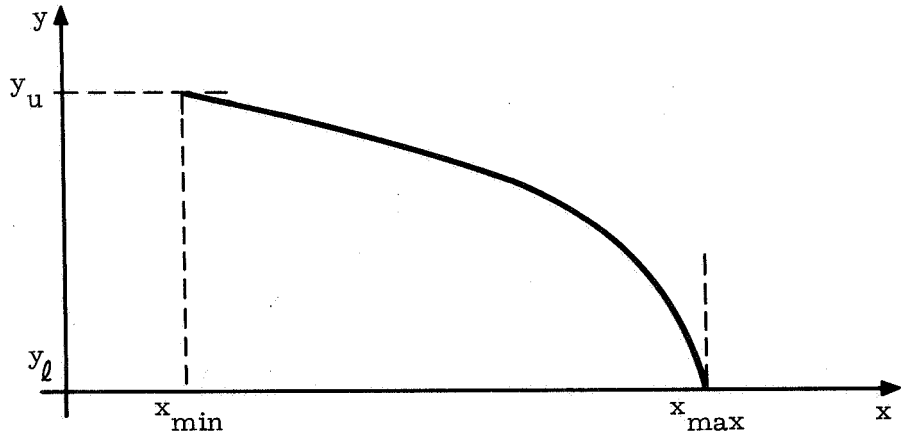


Figure D.4

The curve shown in Figure D.4 is intended to represent a portion of a parabola whose equation is

$$y = y_\ell + \left(\frac{x_{max} - x}{a} \right)^{1/2} , \quad x_{min} \leq x \leq x_{max} , \tag{D.7}$$

where a is a positive constant, y_u and y_ℓ are determined by (D. 4) and (D. 6) respectively, and $x_{max} = \log_{10}[M_e]$. If x_{min}, the logarithm of the cumulative mass ejected at speeds in excess of v_{max}, is known, then "a" is determined by

$$a = \frac{x_{max} - x_{min}}{(y_u - y_\ell)^2} . \qquad (D.8)$$

Alternatively, the parameter, a, can be determined by requiring that a certain fraction of the impact energy be given over to the kinetic energy of the crater ejecta. Then, (D. 8) can be used to determine x_{min}. The first of these two alternatives is, of course, the easiest way to proceed. GS&M suggest that the cumulative mass ejected at speeds in excess of v_{max}, here denoted by m_{min}, scales according to the square of the impact speed for impacts in hard basalt. However, it is not clear that the use of such a scaling law would be correct for the kinds of impact being considered here (projectiles having masses of the order of 100 kgm impacting on targets of relatively low bearing strength). In a paper by D. E. Gault and E. D. Heitowit [46] the same data as that presented by GS&M is used to conclude that 43 to 53 percent of the projectile kinetic energy goes into the kinetic energy of crater ejecta. It is not definitely known whether the partition of impact energy in materials of relatively low bearing strengths yields a radically different fraction for the kinetic energy of crater ejecta, but rough calculations based on the impact event described in Appendix D have lead the author to believe that something of the order of 50 percent of impact kinetic energy for the kinetic energy of crater ejecta would, if anything, be an overestimate. Actually, it will turn out that according to the present model there is little difference in the long-range dispersal of ejecta if the choice to be made is between 40 and 50 percent; the major difference occurs in the deposition pattern of mass falling within several hundred meters of the impact point and is dictated mainly by the choice of v_{min}. Furthermore, it also happens that a choice of 0.40 for the fraction of impact energy going into crater ejecta kinetic energy leads, under the present model, to a value of the mass ejected at speeds in excess of v_{max}, which is in rough agreement with the value of the same quantity as obtained by applying the scaling law suggested by GS&M.

In order to substantiate some of these claims, first note that the cumulative mass-versus-velocity spectrum may be solved from (D.7) directly. It is of a particularly simple form; namely:

$$m(> v) = M_e \exp\left\{(-a/c)\left[\log_{10}\left(\frac{v}{v_{min}}\right)\right]^2\right\} . \qquad (D.9)$$

The constant $c = \log_{10} e = 0.43429 \ldots$. The amount of mass ejected with speeds between v and v + dv is just $-dm(> v)/dv$, and so the kinetic energy going into crater ejecta, K_e, is

$$K_e = -\frac{1}{2}\int_{v_{min}}^{\infty} v^2 \frac{dm(> v)}{dv} dv ,$$

or, upon using (D.9) and integrating by parts,

$$K_e = \frac{1}{2} M_e v_{min}^2 \left(1 + \sqrt{\frac{\pi}{ac}}\, e^{1/ac}\left[1 + \mathrm{erf}(1/\sqrt{ac})\right]\right) ,$$

where erf(x) is the Error Function,

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-w^2} dw .$$

Since the excavated mass, M_e, is directly proportional to the impact energy according to (D.1), the fraction of the impact energy given over to the kinetic energy of the crater ejecta, $f = K_e \Big/ \left[(1/2) M V_i^2\right]$, must be

$$f = \frac{k_1}{2} v_{min}^2 \left(1 + \sqrt{\frac{\pi}{ac}}\, e^{1/ac}\left[1 + \mathrm{erf}(1/\sqrt{ac})\right]\right) . \qquad (D.10)$$

If one takes f = 0.4, $v_{min} = 10^3$ cm/sec, and k_1 according to (D.2), one finds that

$$a = 0.66 \ . \tag{D.11}$$

All of the necessary ingredients for a calculation of the dispersal of the crater material are now at hand. Equation (D.9) expresses the cumulative mass-versus-ejection speed distribution, Equation (D.3) gives the ejection angle, β, as a function of ejection speed, and by adaptation of formula (C.13) from Appendix C, we have the range s along the moon's surface from the primary impact point to the secondary impact point of a piece of crater ejecta, given as a function of the angle and speed of ejection:

$$s = R\pi - 2\,R \tan^{-1}\left(\frac{\rho^{-1} - \cos 2\beta - 1}{\sin 2\beta}\right). \tag{D.12}$$

(However, note that here the ejection angle, β, is the angle of ejection measured from a plane tangent to the moon's surface at the point of impact.)

In principle, the inverse of (D.9) can be substituted in (D.3) to give the ejection angle as a function of the cumulative ejected mass, and this latter result together with ρ expressed in terms of the inverse of (D.9) can be substituted in (D.12) to give the range as a function of the cumulative ejected mass. This final result is then inverted to give

$m(> s)$ = cumulative mass of crater ejecta having secondary impact points at ranges greater than s .

In practice, the calculation mentioned above that obtains $m(> s)$ is best performed numerically. Moreover, the most useful quantity for the purposes of estimating the dispersal of microorganisms is not the cumulative mass of crater ejecta to be found at distances greater than some given distance s, but is the surface density of crater material thrown out from a given impact as a function of the distance from the point of impact. The surface density, which will be denoted by $\sigma(s)$ and measured in units of gm/km^2, is given by

$$\sigma(s) = \frac{1}{2\pi R \sin\left(\frac{s}{R}\right)} \left| \frac{dm(> s)}{ds} \right| \tag{D.13}$$

where R is the radius of the moon (1738 km) and s is measured in kilometers.

The graphs of $\sigma(s)$ versus s for several impacts that are shown in Section IV have been obtained via a numerical scheme based on the method outlined in the preceding paragraphs.

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