NASA SP-344

Objectives and Models of the Planetary Quarantine Program

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Morton Werber

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FOREWORD

This is one of two reports dealing with the events leading to the establishment of a Planetary Quarantine Program in the United States, the development of this program, and its status as of the summer of 1973. The reports partially fulfill the National Aeronautics and Space Administration's (NASA's) requirement that the program be recorded fully so that research and development need not be repeated in the future. Both were prepared for the NASA Planetary Quarantine Office by the Science Communication Division of the George Washington University Medical Center, under Contract NSR 09–010–027. The other report, written by Charles R. Phillips and entitled *The Planetary Quarantine Program, 1956–1973: Origins and Achievements* (NASA SP–4902), has been published in the NASA historical series.

Now that the Apollo Lunar Exploration Program has come to a halt, at least temporarily, and the exploration of the planets is proceeding on an established, although not accelerated, basis, it is time to take stock of where we stand today.

One of the most exciting possible discoveries in space exploration would be the detection of extraterrestrial life. The Planetary Quarantine Program, both national and international, is an outgrowth of great scientific concern that the search for such life might be compromised by terrestrial microbial contamination during early space exploration projects before effective life detection systems can be added to the space program.

The very term "planetary quarantine" shows how the program has expanded. The first discussions and efforts used the term "sterilization." Then sterilization, an absolute term, was gradually replaced by "probability of contamination." The consideration that in cases where microorganisms could not be killed they could possibly be confined led to the concept of "quarantine." When trajectory control came into use, flybys could be kept at sufficient distance from celestial bodies to avoid transfer of contaminants, while getting close enough to gain significant scientific information.

The Phillips report outlines United States effort in planetary quarantine, beginning with the expressions of alarm by biologists, then discussing how a program was put together and implemented, and finally indicating the academic, governmental, institutional, and industrial agencies and people involved. It ends with a brief summary of the accomplishments and present status of the Planetary Quarantine Program.

The present report by Morton Werber goes more deeply into the statements of objectives or goals, general at first, and then deals with the development of sophisticated models which furnished the basis for establishing national and international policies. It will, we trust, serve as a partial explanation of how the planetary quarantine effort evolved and reached its present position.

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CONTENTS

CONTAMINATION PREVENTION—BEGINNINGS

One of the earliest attempts to establish and implement a program to prevent contamination of the Moon and planets by terrestrial microorganisms occurred at the VIIth International Congress of the International Astronautical Federation (IAF) held in Rome in September 1956 (Haley, 1963). The IAF attempted to coordinate international efforts to prevent interplanetary contamination when the first space flight was made in 1957. This led to formation of the International Institute of Space Law, an IAF subsidiary with 11 working groups, each concerned with a different aspect of space law.

Some of the initial attempts to deal with contamination and sterilization problems, in addition to those of the IAF, were carried out by the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS). The committee included representatives from governments and from the Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU). UNCOPUOS was an outgrowth of an ad hoc committee on the peaceful uses of outer space (formed December 13, 1958), that was boycotted by several governments.

A report published by the committee on July 18, 1959, expressed apprehensions that (Haley, 1963, p. 289)

> . . . activities in outer space might bring to those regions, by inadvertence, living or other matter from the earth capable of interfering with orderly scientific research. It was agreed that further study should be encouraged under appropriate auspices to specify the types of risks, the gravity of dangers, and the technical possibilities, as well as the cost of preventive measures. Such a study should also cover safeguards against similar contamination as well as protection against other hazards to health and safety that might be created by the carrying out of programmes to explore outer space.

A subsequent statement proposing the possible formation of international standards was added on June 11, 1959. But, as Haley observed, because the latter was stated weakly, considered a legal problem not requiring priority treatment, and lacking in support by some governments the report was of limited value.

In 1957, the U.S. National Academy of Sciences (NAS) expressed its concern with the problems of interplanetary contamination resulting

from space exploration. The necessity for international cooperation to prevent alteration or destruction of extraterrestrial life forms was recognized. The possibility that "initial space explorations might compromise and make forever impossible certain scientific investigations on the chemistry and biology of the planets" (Bruch, 1968, p. 686) led Dr. Detlev W. Bronk, president of NAS, to recommend in late 1957 the formation of a Satellite-Life Sciences Symposium. He recommended further that the chairman of the Earth Satellite Panel of the U.S. National Committee/International Geophysical Year serve as chairman of the planning committee.

On February 8, 1958, the Council of the NAS adopted the following resolutions (*Science*, 1958, p. 887):

> The launching of IGY satellites has opened space to exploration. Accordingly, attempts to reach the moon and planets can be anticipated, with reasonable confidence, within the foreseeable future.
>
> The National Academy of Sciences of the United States of America urges that scientists plan lunar and planetary studies with great care and deep concern so that initial operations do not compromise and make impossible forever after critical scientific experiments. For example, biological or radioactive contamination of extraterrestrial objects could easily occur unless initial space activities be carefully planned and conducted with extreme care.
>
> The National Academy of Sciences will endeavor to plan lunar or planetary experiments in which the Academy participates so as to prevent contamination of celestial objects in a way that would impair the unique and powerful scientific opportunities that might be realized in subsequent scientific exploration.
>
> The Council of the National Academy of Sciences of the United States of America urges the International Council of Scientific Unions to encourage and assist the evaluation of possibilities of such contamination and the development of means for its prevention. The Council of the Academy also requests the International Council of Scientific Unions to do whatever else it may to preserve and foster the unaffected potentialities of space research.

These resolutions were communicated to the ICSU Bureau by Lloyd V. Berkner, ICSU President, during its meeting on March 3–5, 1958. As a result, an ad hoc Committee on Contamination by Extraterrestrial Exploration (CETEX), with Marcel Florkin as president, was established by the ICSU, which met at The Hague, May 12–13, 1958. The committee presented its report urging the acceptance of a code of conduct that would provide some compromise between maximum efforts toward lunar and planetary exploration and constraints to protect celestial bodies for future research.

The committee also discussed problems dealing with the Moon's atmosphere, Moon dust, cosmic dust, the panspermia hypothesis, contamination of the Moon by living cells, development of complex molecules, and contamination of Mars and Venus. The report proposed that ICSU members prepare papers on these problems by the end of 1958. These papers would then be available for the second CETEX meeting, where additional recommendations would be made. In discussing con-

tamination, it was stated that the absence of water on the Moon caused by high vacuum precluded the possibility of cells such as spores or bacteria giving rise to life of the same kind on the Moon. However, it was recognized that a greater probability of such growth on Mars, and possibly on Venus, necessitated adequate measures to prevent contamination.

The Satellite-Life Sciences Symposium was held in Washington, D.C., May 14–17, 1958, under the sponsorship of the NAS, the American Institute of Biological Sciences (AIBS), and the National Science Foundation (NSF). At the meeting on "Possible Uses of Earth Satellites in Life Science Experiments," Joshua Lederberg delivered a paper on the dangers of lunar contamination (Lederberg and Cowie, 1958). Lederberg pointed out that the Moon may be covered by a very old layer of dust captured by its gravitational field. "For the biologist, this dust may furnish two striking opportunities: (i) to assess the prebiotic synthesis of organic compounds and (ii) to make an empirical test of cosmic dissemination of biospores [Arrhenius' *pan*-spermia hypothesis]" (Lederberg and Cowie, 1958, p. 1473). However, the potential benefits of such opportunities require considerable care in planning space probes. He cautioned that if contaminants were introduced to the Moon by spacecraft, an interpretation of a test of Arrhenius' hypothesis would be very difficult. Lederberg noted that the surface area of the Moon is $4 \times 10^{13} m^2$, and that in contaminated material microbial populations can readily reach a level of 10^{13} micro-organisms per kilogram.

The Space Science Board (SSB), formed in June 1958 by the president of NAS, was one of the recipients of the first CETEX report, circulated in July 1958, with a request for comments. The SSB had been formed to "serve as the focal point for the interests and responsibilities of the Academy-Research Council in space science" (Derbyshire, 1962, p. 10:13). A meeting was held in December 1958, under the sponsorship of the SSB, to consider various problems concerned with the detection of extraterrestrial life and the prevention of contamination of extraterrestrial bodies by terrestrial organisms. This group, composed of representatives of the biological, astronautical, physical, and engineering sciences, became EASTEX. A comparable west coast group, WESTEX, was later established by Joshua Lederberg. WESTEX held several meetings during 1959, recognizing as the primary problem, the formulation of requirements for space probe sterilization from the standpoint of biology. On May 7–9, 1959, the SSB requested that an ad hoc committee be formed to work toward this objective. The committee later found that sterilization was feasible and that effective methods could be developed. The SSB adopted the findings of the committee and sent them to the appropriate Federal agencies on September 15, 1959.

The first instance of these recommendations being put into effect is reported in a letter dated October 13, 1959, from T. Keith Glennan,

Administrator of NASA, to Hugh Odishaw. Glennan agreed with the SSB recommendations, and NASA gave instructions for the Space Technology Laboratories to sterilize the *Atlas-Able* 4 lunar orbiter payload; for the Goddard Space Flight Center to sterilize the lunar miss payload Delta P–14; and for the Jet Propulsion Laboratory (JPL) to develop sterilization procedures for all lunar Vega probes.

The SSB, together with those Federal agencies responsible for various aspects of the space program, also reviewed and endorsed the CETEX report and assured NAS and launching agency support for the CETEX recommendations.

FORMATION OF COSPAR

In October 1958, ICSU accepted the CETEX recommendation for the establishment of a code of conduct for space missions and research. A second meeting (CETEX II) was called for March 9–10, 1959. The committee believed that immediate action was necessary in order to deal effectively with the contamination problem (Trauth, 1968, p. 135).

> In its lifetime (1958–59), this Committee recognized two principles which have had considerable influence upon the international approach being taken to planetary quarantine. The first was that *certain* knowledge that a planet is not contaminated was, in all likelihood, possible only if that planet was avoided by space vehicles. The second was that exploration of the planets *would* take place, and that the nations involved in such exploration would determine their own time schedules for this exploration.

The CETEX II meeting was held at The Hague, with Marcel Florkin as convenor. In October 1958, between the first and second CETEX meetings, the ICSU had formed a Committee on Space Research (COSPAR) to coordinate worldwide space research. The formation of COSPAR was a continuation of the cooperative efforts in space research begun during the International Geophysical Year by the Comité Spécial de l'Année Géophysique Internationale. The SSB, through the NAS, gave full support to COSPAR, and W. Albert Noyes, Jr., Chairman of the SSB Committee on International Relations, was appointed U.S. delegate to COSPAR. He was later succeeded by Richard W. Porter.

COSPAR had the support of both the U.S. and U.S.S.R. Academies, and CETEX recommended that COSPAR assume responsibility for the contamination problem. Thus, the problem was referred to COSPAR, a permanent ICSU committee.

CETEX also reviewed its earlier report concerning such problems as the panspermia hypothesis and the biological contamination of the Moon, Mars, and Venus and suggested that COSPAR initiate an immediate study of methods for sterilizing the interior of a spacecraft without harming its delicate instruments. The committee's report also stated that there was no need to sterilize the outer surface of space vehicles,

since micro-organisms on the ship's shell would be exposed to unfiltered solar radiation during flight. Furthermore, it was felt that the need for sterilization was only temporary, and the requirement that Mars and Venus remain uncontaminated was necessary only until a study could be made with manned spacecraft.

At its meeting on March 12–14, 1959, COSPAR acknowledged the CETEX II report and recommendations and assumed responsibility for this area of concern. At the same time, COSPAR requested that the U.S. and U.S.S.R. consider ways of avoiding contamination. The request was communicated to the SSB by the U.S. delegate to COSPAR.

During the period immediately following the COSPAR meeting, several reports presenting analyses of various aspects of contamination and sterilization were written. For example, Davies and Comuntzis (1960) acknowledged the possibility of indigenous life on Mars and Venus and that the environments of those planets might support rapid proliferation of terrestrial micro-organisms. They warned that the introduction of terrestrial organisms might result in an irreversible scientific catastrophe, noting that if the Earth were sterile, it would require only a matter of months or years to populate it with the decendants of a single cell. *E. coli*, with a mass of 10^{-12} grams and a fission interval of 30 minutes would, under ideal conditions, require 66 hours to equal the Earth's mass. This illustrates the exponential growth rate of bacteria and emphasizes the urgency of the problem.

BIOLOGICAL CONTAMINATION

Davies and Comuntzis defined two types of biological contamination: pollution and infection (Davies and Comuntzis, 1960, p. 498).

> Biological pollution is meant to be a deposit of a large enough number of micro-organisms to be scientifically significant, as such, without further growth. Infection is meant to describe the growth of one or more viable organisms. Likewise, pollution can be divided into two categories: viable pollution, which does not grow by nature of its environment, and nonviable pollution.

Pollution is that form of contamination that could occur on the Moon, Mars, and Venus if, for example, an animal were involved in the crash of a spaceship on their surfaces. Davies and Comuntzis estimated that a mammal's intestines can contain 10^{12} micro-organisms per kilogram, and perhaps 10^{13}, if it died during flight. Since the Moon's area is 4×10^{13} square meters, and with 1960 improvements in methods permitting detection of one micro-organism to perhaps better than one per square meter, a residue of from 10^{9} to 10^{10} dead terrestrial bacteria could interfere with future research. The authors suggested that infection is least probable on the Moon because of the lack of water; that Mars is more promising in terms of both infection and basic biological research; and

that any theorizing about Venus would be premature. Abelson (1961; cited in Bruch, 1968, and in Haley, 1963) went even further by proposing that it was almost impossible to biologically contaminate or infect the Moon, Venus, or Mars. Abelson, who was a consultant to NASA from the Geophysical Laboratory of the Carnegie Institution of Washington, agreed that adopting a new set of sterility restraints would cost $10 million and impede the American space program to a significant degree.

Davies and Comuntzis maintain, however, that probe sterilization might be mistakenly regarded as unnecessary by those who stress the effects of the Sun's ultraviolet radiation, space vacuum, the Moon's high surface temperatures, the heat of impact or impact explosion, and the heat of entry into a planetary atmosphere. They also point out that the cracks and fissures on the surfaces of the Moon and planets would serve to protect terrestrial micro-organisms from high temperatures or ultraviolet radiation and that laboratory vacuum can help preserve these organisms. In addition, they suggest that some areas of the probe will never be exposed to sunlight, and ultraviolet radiation will not destroy micro-organisms unless they are nakedly exposed. Further, an organism can survive if surrounded by a small number of dead ones. Finally, as for the heat of impact or impact explosion, a hard landing on the Moon would have an impact velocity of 3 kilometers per second, which is not sufficient to melt or vaporize the probe.

The authors therefore conclude that the problems of contamination and probe sterility should be viewed within the context of probabilities, and the exponential death rate of micro-organisms subjected to lethal treatment (Davies and Comuntzis, 1960, p. 503).

> For Mars and Venus, the consensus [of biologists in the United States] is that the probability of landing one viable organism should be less than one in a million. This means that, if the probability of successfully impacting a probe were judged *a priori* to be one in a hundred, it would be necessary to sterilize the payload to a tolerance of one chance in ten thousand that it have a live organism.

In regard to the Moon, they tentatively recommend an infection tolerance of one chance in 10 or possibly in 100, of a viable micro-organism remaining on the probe. They also believe that pollution should be kept to less than 10^8 dead organisms per probe for both the Moon and the planets.

Several other papers having important implications for the development of contamination control guidelines appeared at the same time. For example, Lederberg stated (Lederberg, 1960, p. 398):

> The introduction of microbial life to a previously barren planet or to one occupied by a less well-adapted form of life, could result in the explosive growth of the implant, with consequences of geochemical scope. With a generation time of 30 minutes and easy dissemination by winds and currents, common bacteria could occupy a nutrient medium the size of the earth in a few days or weeks, being limited only by the exhaustion of available nutrients.

It follows that we must *rigorously* exclude terrestrial contaminants from our spacecraft.

According to Lederberg, the ubiquitous nature of bacterial spores and their durability under adverse conditions, such as high vacuums and low temperatures, must be fully appreciated in order to prevent contamination.

Sagan (1960) emphasized that biological contamination of the Moon would be an unparalleled scientific disaster, severely affecting efforts to study the early history of the solar system, the origin of life on Earth, extraterrestrial life, and the chemical composition of matter in the remote past. In his study, Sagan considers three primary factors in regard to the survival of terrestrial life on the Moon: temperature, corpuscular radiation, and solar electromagnetic radiation. He does not believe that the absence of oxygen, water, and other substances from the Moon's surface would prohibit survival, especially of dormant anaerobic micro-organisms; however, he thinks that this would preclude their reproduction.

MICROBIAL SURVIVAL

Insofar as the effect of temperature on the survival of micro-organisms is concerned, Sagan hypothesizes that it would have no debilitating effect, since most of the organisms would be deposited just beneath the Moon's surface, where the temperature would range between 0° and −70° C at a depth of less than half a meter.

Sagan estimates that a 1 kg. instrumented lunar package could contain 10^{10} micro-organisms, with little likelihood of this figure's being 10^{20} organisms for packages in the immediate future. With these limits, he presents the following equation:

$$t = 214ap\ (D/I)\ [1 - e^{-(\mu/p)p^a}]^{-1}\ \log_{10}(N_0/N)$$

where (μ/p) is the mass absorption coefficient of the organism in cm.^{2} gm.$^{-1}$ and p is its density in gm. cm.$^{-3}$. The time t (in seconds), in which a population of N_o organisms with a mean lethal dose D for a given radiation and the diameter, a (in centimeters) is reduced to N organisms by radiation of intensity 1 erg cm^{-2} s^{-1}. Sagan states the following (Sagan, 1960, p. 398):

For ionizing radiation, the high value of $D = 10^7$ rep was chosen. For ultraviolet radiation, a mean value $D = 10^7$ erg cm^{-2} was selected for 2000 Å $\leq \lambda \leq$ 3000 Å: for $\lambda \leq$ 2000 Å, $D < 10^6$ erg cm^{-2}.

It should be emphasized that these mean lethal doses are purposely high to allow for anaerobiosis and drying. The resulting lifetimes should be upper limits, except, perhaps, where $p/\mu \ll pa$ for ionizing radiation.

Thus, with these limits on N_o/N, all of the deposited micro-organisms

exposed to the Sun would be killed by ultraviolet radiation within a few hours. But those organisms deposited in a lunar crevasse or depression, so as to be shielded from solar radiation, would be killed only by cosmic rays and natural radioactivity. At the high value of D, micro-organisms just below the lunar surface and shielded from the Sun would survive for a few hundred million years. Therefore, with what was known about the Moon's surface in 1960, it could easily be assumed that dormant anaerobic micro-organisms could be deposited in a way so as to protect them from the Sun's rays at all angles of incidence and ensure survival of at least some for very long periods of time.

Davis and Fulton (1960) were, perhaps, the first to report on the validity of the assumption that possible Martian life was similar to certain types of simple terrestrial life. Interest in such work increased during this period, as the possibility of extended space flight became more feasible. The authors employed the environmental conditions outlined in Table 1 in their experiments, even though these limits were not identical to those believed to exist on Mars. They were, however, thought to be similar enough to provide meaningful data regarding the contamination of Mars by simple forms of terrestrial life such as those which would be deposited by contaminated space probes.

Table 1 *Simulated Martian Environment (after Davis and Fulton, 1960).*

Factors	Simulated by
Atmospheric pressure	65 mm. Hg.
Moisture content	Approx. 1%
Atmospheric composition	Commercial nitrogen gas
Soil type	Red sandstone, lava soil
Temperature range	+25° to −25° C
	Diurnal Nocturnal

The results of the Davis and Fulton experiments showed:

1. Soil bacteria, selectively adapted to a simulated Martian environment, survive and multiply.
2. Sporeforming bacteria appear to have a higher rate of cell multiplication than strictly vegetative cells.
3. A simulated Martian environment, including temperature cycling, an environmental characteristic on Mars, appears to yield greater numbers of viable cells than a simulated Martian environment under room temperature conditions.

Somewhat later, Hawrylewicz et al. (1962) reported that an encapsulated anaerobic organism such as *K. pneumoniae*, the spores of

anaerobic organisms such as *Cl. botulinum*, and possibly the tetanus and gangrene organisms could survive simulated Martian conditions. Packer et al. (1963) also demonstrated that terrestrial micro-organisms collected in soil samples from a variety of environments (e.g., regions of high alkalinity, low temperatures, and scant rainfall) survive under conditions simulating those on Mars.

STERILIZATION OF SPACE VEHICLES

An article by Phillips and Hoffman (1960) is of special interest. It concerns the need for sterilizing interplanetary vehicles, the resistance of life forms in space, and techniques of sterilizing space vehicles without restricting the mission or interfering with operation of the vehicle. The authors describe experiments carried out at Fort Detrick to determine whether various components of a vehicle were contaminated with living micro-organisms when received from the manufacturer, and whether assembly techniques would further entrap such organisms. It appeared that such contamination was present, leading to the assumption that all components of the spacecraft contained internal bacterial contamination. The ability of the components to function satisfactorily after being subjected to various sterilization procedures was also investigated. On the basis of the available data, the authors concluded that a space vehicle could be sterilized only with sufficient attention to the sterilization requirements at all stages of design and construction.

Some of these problems were more fully explored in a conference, Problems and Techniques Associated with the Decontamination and Sterilization of Spacecraft, sponsored by NASA and held June 29, 1960. During the discussions, participants recommended that (Posner, 1961, p. 39)

1. A body of information relating to sterilization techniques and procedures be built up and made available to all interested parties currently working in this area or who may be involved in the future.
2. A standard operating procedure be established for each scheduled launch at a stage early enough to include decontamination or sterilization as an environmental factor for design considerations.
3. Studies be made relating to the sterilization of explosive squibs.
4. Work be done in the area of determining the probabilities of inadvertent impact, coupled with the statistical limitations of implanting live micro-organisms on celestial bodies.
5. NASA further clarify its policy and intent with respect to decontamination and sterilization.
6. An increased effort be put on the development of new and better sterilizing agents that will more closely meet engineering requirements.

7. Efforts be extended at the same time towards developing structures and component parts that are compatible with sterilizing agents.
8. The manufacturing process be studied to determine the feasibility of producing materials and components that are internally sterile.
9. A group at the working level be established to discuss details and problems of implementing sterilization techniques.

At another conference on spacecraft sterilization held July 9, 1962, under the auspices of the NASA Biosciences Programs (Quimby, 1962), George Hobby of JPL, who was cochairman of the conference with Orr Reynolds (NASA Headquarters), discussed tolerance levels. The probability that a single viable micro-organism remained after a spacecraft or one of its components had been subjected to a sterilization procedure was considered. Hobby pointed out that the original probabilities derived by the WESTEX committee were as low as 10^{-6}, but that this was reduced to 10^{-4}, which was considered a safe level. In effect, as Reynolds noted, this meant that only one out of 10 000 landings or impacts on Mars, for example, would contain a micro-organism. In the discussion of this probability level, Richard Price stated (Quimby, 1962, p. 16):

> People who would like to see the limits slided to one side or the other have interpreted it [10^{-4}] to mean out of 10000 organisms per capsule, per vehicle, one of them would be alive.

However, Hobby's interpretation is different; he observes that there would be more than 10,000 organisms per spacecraft (Quimby, 1962, p. 16).

> It is really what the probability is that no matter how many you have, after applying the sterilization technique you will have one remaining.

Many comments at this conference centered around a report by L. D. Jaffe of JPL, who was on temporary assignment with the NASA Lunar and Planetary Office during 1962. The report was sent to those attending the conference and aroused considerable interest. For example, Charles Phillips stated that Jaffe, on the basis of the best sterilization methods available, had set the current (1962) probability level that could be achieved at 10^{-4} rather than 10^{-6}. Phillips commented that Jaffe's paper was an excellent document in which the 10^{-4} value was shown to be a feasible criterion and that the various steps by which that figure was derived were outlined. However, Hobby felt that the 10^{-4} tolerance had little meaning, and that sterilization should proceed on the basis of utilizing the best available methods and designing them as carefully as possible. He considered it impractical to establish a particular tolerance number for a particular figure. Nevertheless, the 10^{-4} level

was reviewed as a goal and was regarded as desirable in that sense.

CONTAMINATION RISKS

At this point, it is necessary to review Jaffe's position, outlined in a 1963 paper in *Astronautics and Aerospace Engineering.* Jaffe considered that on the basis of tests made with terrestrial organisms under simulated Martian conditions, the chance of growth of some micro-organisms, if released on Mars, appeared to be essentially unity. He outlined two methods by which an acceptable risk of contaminating Mars could be established. First, it could be assumed that this risk should be kept as low as the chance that no useful biological data would be obtained for other reasons. He estimated that for each attempt at reaching Mars, the probability of failure was 50 percent. Similarly, if a space vehicle succeeded in reaching the planet, the probability that no useful data would be returned because of some failure in instrumentation or equipment was possibly 50 percent. Therefore, he estimated that the probability that no useful data on life would be returned on any one space probe was 3/4. Furthermore, the probability that no useful biological data would be obtained in a series of 28 flights (based on two attempted flights by the U.S. and the U.S.S.R. during each of seven oppositions of Mars before 1980) was estimated to be 3/4, or $10^{-3.5}$.

A second method of estimating the chance of contaminating Mars during unmanned flights would be to state that the probability should be kept low relative to the chance of contamination during the first manned landing. The probability of terrestrial micro-organisms being released during a manned flight through such factors as incomplete sterilization or defects in equipment (leaks, fractures, etc.) was estimated by most engineers at 10^{-1} or higher. Thus, Jaffe believed that 10^{-2} would be a low enough number representing the permissible probability of contaminating Mars during the unmanned flight (Jaffe, 1963, p. 22).

The numbers $10^{-3.5}$ and 10^{-2} for a program in which 14 flights reach Mars lead to $10^{-4.6}$ and $10^{-3.1}$ for the permissible probability of contamination on each flight. Perhaps an intermediate value of about 10^{-4} is reasonable.

This figure (10^{-4}) was also suggested by an SSB study (*A Review of Space Research,* 1962) for flyby trajectories as an alternative to sterilization.

Jaffe also considered the required degree of assurance against contamination of Venus by terrestrial micro-organisms, noting that the probability was modified by the chance that Venus does not have an environment suitable for the growth of Earth organisms. He estimated that there was a 10^{-3} chance of terrestrial micro-organisms finding a suitable environment on Venus, since the surface of the planet is very hot and the only regions appropriate for this growth are in the planet's upper atmosphere. Since terrestrial micro-organisms do not seem to multiply

in their own atmosphere, he assumed that there was little chance they would do so in that of Venus (Jaffe, 1963, p. 23).

The chance of some Earth micro-organism finding suitable environment for growth on Venus is therefore estimated at 10^{-3}. Dividing the value of 10^{-4} for assurance against planetary contamination by this 10^{-3} gives 10^{-1} as the suggested assurance against releasing viable micro-organisms into the upper atmosphere of Venus.

Jaffe believed that spacecraft sterility probably was not essential for missions to the Moon, since Sagan (1960) and Imshenetsky (1962), as cited in Jaffe, hypothesized that there was only a remote chance that terrestrial micro-organisms could grow and reproduce on or near its surface. However, Lederberg and Cowie (1958) maintained that it would be desirable not to contaminate the Moon, so that any organic substances found there would not be confused with those brought from Earth. Consequently, Jaffe suggested that the probability of an Earth micro-organism being found on the lunar surface should be held to 10^{-6}/sq. cm. of surface, which would mean that all unmanned flights to the Moon should deposit no more than 4×10^{11} organisms. Instead of sterilization for such lunar flights, he thought that cleanliness procedures should be used, assuring the deposit of no more than 0.01 gram of living matter per flight.

Jaffe's guidelines were revised at the 1962 NASA Conference on Spacecraft Sterilization. These revisions were, in turn, modified by the Iowa City OSSA Space Science Summer Study. The final standards included (Quimby, 1962, pp. 80–81)

1. For mariner buses and booster last stages, either sterilization must be used or trajectories must be controlled to ensure a possibility of hitting Mars of not over 10^{-4} and a probability of hitting Venus of not over 10^{-2}.
2. A mariner entry capsule for Mars should be given recognized and accepted (official) sterilization treatment and handled aseptically thereafter. The goal of these activities should be that there is less than 10^{-4} probability that a single living organism is released on the planet's surface. This figure takes into account the probabilities of sterilization during Mars entry and impact and of releasing organisms from the capsule at the planet.

As early as 1959, the SSB considered the possible contamination of the Moon and planets by the impact of space probes. It adopted recommendations urging study of the contamination problem and sterilization standards and establishment of procedures to ensure a complete inventory of all space probe components. These suggestions comprised the basis for NASA's study of space vehicle sterilization and its policy requiring some degree of sterilization for all space probes passing near, or impacting on, the Moon or planets. The results of this work were

reviewed at the 1962 Space Science Summer Study, and the SSB restated its previous policy with regard to lunar and Martian probes.

The SSB regarded the Moon's surface as highly unfavorable for the growth and survival of terrestrial micro-organisms. However, to avoid possible distortion of chemical evidence by microbial action and contamination of the Moon's deeper layers, it recommended the following (SSB, 1963, p. 2):

1. Minimize contamination to the extent technically feasible. By appropriate selection of components (favoring those that are inherently sterile internally) and the use of surface sterilants, it should be possible to achieve a cleaniness level to approximate that which prevails in most hospital surgery rooms.
2. Inventory all organic chemical constituents. This will permit the interpretation of analytical results from future collections of lunar material.
3. Accord a low priority to life detection experiments by remote devices on the lunar surface. A high priority should be attached to sampling the subsurface at points removed from the immediate vicinity of any landing site.
4. Undertake the development of a sterile drilling system to accompany an early Apollo mission to return an uncontaminated sample of the lunar subsoil. Samples aseptically collected from this subsoil will be of both biological and geochemical interest. Should life exist on the Moon, it might be expected at some depth below the surface where temperatures never exceed 100° C and below the zone of ultraviolet radiation. Every effort should be made to keep this level free of contaminants until it can be sampled by drilling.

On the planet Mars, on the other hand, there is by far the greatest probability of extraterrestrial life. Since terrestrial micro-organisms have been known to survive in simulated Martian environments,[1] contamination and pollution of that planet should be avoided, even if initial indications from remote detectors suggest no biota on the planet. As such, the SSB recommended the following (SSB, 1963, p. 3):

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[1] Scher et al. (1964) suggest that if a random sample of terrestrial soil micro-organisms is deposited on Mars, a significant fraction of their number will survive. Thus, to avoid contamination, entry vehicles should be thoroughly sterilized prior to launch. Hawrylewicz et al. (1965) report that a number of micro-organisms are able to survive conditions simulating those on Mars, but show no substantial growth. In a subsequent study (Hawrylewicz et al., 1966), it was demonstrated that soil microbes can proliferate under very severe conditions; i.e., their vegetative cell growth and sporulation were normal in a simulated Martian environment.

1. Accord the highest priority to the prevention of the biological contamination of Mars until sufficient information has been obtained about possible life forms so that further scientific studies will not be jeopardized. Recognition of this priority on the part of launching nations is in accord with their main scientific objectives, in contrast to a competition to be first, in which these objectives might be forever sacrificed.
2. Establish and provide adequate support for an augmented research program to develop agents, methods, and techniques for the sterilization of Martian probes. Such a research program should mobilize both biologists and engineers to ensure successful development of practical sterilization procedures.
3. Inventory all organic chemical constituents. This is a precautionary measure, but the lack of an inventory might make impossible the interpretation of analytical results from future collections of Martian material.
4. Cooperate fully with all other nations in the protection of Mars against premature biological contamination. The exchange of information and the possibility of a joint research project between scientists of the U.S.S.R. and the U.S. should be explored.
5. Strengthen the current research program for the development of the best possible life detection experiments to ensure the incorporation of a life detection experiment in the first Mars lander. This is of extreme importance, for otherwise we may succeed in the sterilization of Mars probes but fail to accomplish our true objective.

In a letter to *Science* in 1963, Oran W. Nicks and Orr E. Reynolds discussed NASA's policy regarding decontamination and sterilization. Although CETEX and Carl Sagan calculated a low contamination probability for lunar missions, NASA modified its requirements for lunar spacecraft. NASA intended to reduce the microbial load to a minimum through the use of assembly and checkout in bacteriologically clean rooms and the application of surface sterilants after final assembly and checkout (Nicks and Reynolds, 1963, p. 540).

> In this way, contamination, if any, will be localized to very small areas on the Moon; there will be very low probability of microbial proliferation.

As for Mars, it was planned that initial flights be directed so that there would be less than a 10^{-4} probability of encountering the planet. In addition, the landing capsules would be sterilized after complete assembly and checkout, using appropriate procedures and sealed units that would not be opened.

In 1961, ICSU adopted Resolution 10, "Space Experiments with Undesirable Effects." It suggested that COSPAR examine and study any

proposed experiments in space or other activities that might have potentially undesirable effects and make the results of these studies available to those engaging in such experiments. The resolution further recommended that all governments planning to launch space experiments that could have an adverse effect on other scientific research should provide the ICSU with the information necessary to make the studies mentioned.

Harmful Effects of Space Experiments In response to Resolution 10, at its Fifth Plenary Meeting in Washington in 1962, COSPAR organized a Consultative Group on Potentially Harmful Effects of Space Experiments. The group was comprised of six broadly competent scientists from the disciplines of astronomy, radiation physics, atmospheric physics and chemistry, communications, meteorite penetration, and microbiology. The group was to be responsible for studying the potentially harmful effects of proposed space experiments and making appropriate recommendations to the COSPAR Executive Council for further action.

The group met in Paris in March 1963 and in Warsaw in June 1963. A preliminary report submitted to COSPAR at the Warsaw meeting affirmed that the group was concerned with contamination of the Moon and planets, pollution of the upper atmosphere, and orbiting dipoles. Hedén (1964) wrote that at that time all of the organizations belonging to the International Association of Microbiological Societies and various individuals were asked to consider the contamination problem. The consultative group was endeavoring to collect pertinent data on the physical and chemical environments of Mars, Jupiter, Venus, and the Moon, in order to evaluate their biological implications. Replies to this request tended to emphasize the importance of using extreme caution when direct contacts were to be made with the planets, particularly Mars. Furthermore, it was thought that the maximum limit of contamination (10^{-4} for Mars) should be regularly reviewed and, if necessary, revised as additional information became available. However, the following was pointed out (Hedén, 1964, p. 10):

> The uncertainty factors involved [were] obviously so enormously great that the value of mathematical expressions becomes small or even negative because it might tend to lend an air of exactness to interpretations which can hardly be more than educated guesses.

With the background of their discussions concerned with the Warsaw meeting in 1963, a working document for the consultative group was considered. The document recommended that the subcommittee of UNCOPUOS take immediate legal action to have the General Assembly declare Mars a temporary biological preserve, to be approached only by spacecraft subjected to appropriate certified sterilization procedures. Another recommendation was that Venus and Moon probes be sterilized to keep contamination to a feasible minimum. In order to qualify as

certified, sterilization procedures (Hedén, 1964, Appendix 4, p. 1)

> . . . must be proven effective both in surface sterilization and in destroying or removing viable, resistant spores entrapped in or between solids or semisolids or contained in liquids which have no inherent sterilizing capacity.

It was also suggested that the revised Jaffe guidelines be accepted as a provisional international code providing, among other things, the following (Hedén, 1964, Appendix 4, p. 3):

1. Either sterilization must be used, or trajectories must be controlled to ensure a probability of not over 10^{-4} of hitting Mars and a probability of not over 10^{-2} of hitting Venus.
2. An entry capsule for Mars should be given recognized and accepted (official) sterilization treatment and handled aseptically thereafter. The goal of these activities should be that there is less than 10^{-4} probability that a single living organism is released on the planet's surface. This figure takes into account the probabilities of sterilization during Mars entry and impact and of releasing organisms from the capsule at the planet.

Wright (1967b) observed that the recommendations made at Warsaw in 1963 were to become a part of NASA's Planetary Quarantine Program. He referred specifically to the suggestions that Venus and Mars landers should be sterilized before launch, that Venus and Mars flybys should have a trajectory so that the probes and all ejecta would miss the planets, and that decontamination of lunar landers would be acceptable in place of sterilization, in view of the hostile nature of the lunar environment for terrestrial micro-organisms.

At the COSPAR meeting in Florence in May 1968, Hedén convened a study group on sterilization standards for space probes in response to a request of the Consultative Group on Potentially Harmful Effects of Space Experiments. The basis for discussion at the meeting was a report by Sagan and Coleman (1965), which attempted to analyze the probability of contamination and to suggest sterilization standards. The authors' purpose was to provide a means whereby the level of spacecraft sterility would be calculated as a function of an acceptable level of risk of planetary contamination. They noted that in 1960, Davies and Comuntzis had arbitrarily suggested that the probability of landing one viable micro-organism on Mars should be less than 10^{-6} for each mission, and that Jaffe, in 1963, revised this to read $\sigma \simeq 10^{-4.6}$, with σ representing the mean number of viable micro-organisms. They pointed out, however, that Jaffe did not consider the desirability of having a great number of biological experiments on Mars before a significant contamination risk could be allowed, and that not every terrestrial organism deposited on Mars would be capable of contaminating a sizable fraction of the planet.

Contamination Probabilities Sagan and Coleman (1965) demanded a probability very close to unity that N biological experiments be successfully completed on Mars before biological contamination occurred. They considered the probabilities of scientific success and biological contamination per mission as independent events. They specified N as the desired number of experiments for a thorough survey of Martian biology. This value was necessarily large because of the time and effort required to systematically study any Martian organisms.

Initially, they assumed that there would be one experiment for each landing capsule. In $P_+ = P_t P_1$, P_+ is the mean probability that a landing capsule on Mars will successfully perform its biological experiment; P_t is the probability of complete engineering success; and P_1 is the probability that some form of life susceptible to study by the experiment will be discovered on an accessible area of the Martian surface.

P_- represents the mean probability that Mars will be contaminated by a specific landing capsule. The mean number of organisms deposited is σ, and the chance that a specific organism deposited on Mars' surface will multiply and contaminate a large fraction of the planet is given as P_m. Thus,

$$P_- \simeq aP_m$$

Sagan and Coleman believe that there is little chance that life will be found on every Mars mission and that there will be $M > N$ number of missions before one will be successful. They consider the $(N+j)th$ mission, and assume that it is the final in the series of N experiments. Thus, the $(N+j)th$ experiment must be successful because, by hypothesis, they were content to risk a probability, p, that biological contamination of Mars would occur after $N+j$ missions. The remaining missions can be arranged in any order, allowing $(N+j-1)!$ permutations of them. Of these, $N-1$ will be experimentally successful, where again the order, for which there are $(N-1)!$ possibilities, is immaterial. At the same time, j missions will be failures, and once again the ordering of the failures is unimportant. Further, they stated that there must be no contamination events in $N+j$ missions. The total number of ways of obtaining such scenarios of successful experimentation before contamination will be

$$p = \sum_{j=0}^{\infty} P_+ (N+j-1)! \times \frac{P_+^{N-1}}{(N-1)!} \frac{(1-P_+)^j}{j!} \times (1-P)^{N+j} \qquad (1)$$

Here, p is the probability that biological contamination does not occur until N experiments are performed. From the power series expansion

for $(l-y)^{-N}$, they derive:

$$p=\left[\frac{\mathrm{P}\ (1-P_-)}{1-(1-P_+)\ (1-P_-)}\right]^v \tag{2}$$

Thus far, the total number of biological experiments (N) was identical to the total number of missions. However, if there were more than one experiment per mission, one must distinguish between failure of a specific experiment as part of the total mission and failure of the whole mission. In place of equation (2), they used

$$\frac{P_+\ (1-P_-)}{1-(1-P_+)\ (1-P_-)}=px^N \simeq 1+(x\ln p)/N \tag{3}$$

Here, χ is the mean number of experiments per mission and P_+ is the probability of a successful landing.

P_1 is the probability that a specific experiment will be successful, based on the assumption that the mission lands successfully. They assumed that all of the experiments in the mission would succeed or fail together ($P_1=1$). Then, N/χ is the number of successfully landed missions. $(\chi\ \ln\ p)/N$ is negative and small, with P_- of the same magnitude. Keeping the terms of the first order, they arrived at

$$P_- \simeq P_+ \frac{\chi}{N} \ln p^{-1} \tag{4}$$

By substituting from the definition of P_+ and P_-,

$$\sigma \simeq \frac{\chi P_t P_l}{P_m N} \ln p^{-1} \tag{5}$$

A more direct manner of obtaining equation (5), according to Sagan and Coleman, is to calculate the average probability p of the success of N experiments before contamination occurs. P_- is small, and thus p varies slowly as a fraction of the number of successful landings on Mars. In addition, the probability distribution of landed missions tends to cluster about its mean value, $N/P_{+-}\chi$, since N is rather large. The average probability of success prior to contamination may be replaced by its value at the mean, so that

$$p=(1-P_-)^{N/p}{}_+\chi \tag{6}$$

Taking the logarithm of both sides, they arrived at the equivalent of equation (5):

$$\ln p = \frac{N}{P_+ \chi} \ln (1 - P_-) \simeq \frac{P_- N}{P_+ \chi} \tag{7}$$

Then they generalized this equation to the case of $P_e \neq 1$, with $N/P_+ P_e \chi$ the mean number of missions landed. Equation (5) is then replaced with

$$\sigma \simeq \frac{\chi P_e P_t P_l}{P_m N} \ln p^{-1} \tag{8}$$

The probabilities discussed thus far by Sagan and Coleman apply to landing vehicles and not to spacecraft intended for flyby or orbit. In the latter case, accidental landing on the planet's surface may constitute a contamination hazard, particularly if the vehicles are not sterilized. The authors suggest that there may be $\sim 10^{10}$ micro-organisms on such vehicles, and a sizable number (f) would be deposited on the surface following impact. They concluded that since the conditions of impact would not kill all of the organisms, there would be a good chance that the planet would be contaminated on the basis that $fP_m \geqslant 10^{-10}$. Therefore, they calculated that the probability of contamination by a flyby or orbiter would be P_i (the chance of an accidental impact on the planet).

The authors assumed that the biological contributions made by landers would be significantly greater than those made by flybys and orbiters. With n as the number of flybys and orbiters landed during the same period as landers, they extended equation (6) as

$$p = (1 - P_-)^{N/P_+ \chi} (1 - P_i)^n \tag{9}$$

Therefore,

$$\ln p^{-1} \simeq \frac{\sigma N P_m}{\chi P_e P_t P_l} + n P_i \tag{10}$$

By arbitrarily assuming that the contamination risk for flybys and orbiters is the same as that for landers, Sagan and Coleman were able to determine the numerical constraints on σ and P_i. The result is the requirement for landers (equation 11) and for unsterilized flybys and orbiters (equation 12).

$$\sigma < \frac{\chi P_e P_t P_l}{2 P_m N} \ln p^{-1} \tag{11}$$

$$P_i < \frac{\ln p^{-1}}{2n} \tag{12}$$

Sagan and Coleman further assumed the mean number of experiments per mission for the complete program to be $\chi \simeq 20$, and $1-P_t \simeq 0.1$ to be the mean probability of spacecraft failure during the program, so that no significant biological data are obtained from an entire mission. Thus, the mean probability of a given experiment's scientific success is $\simeq 10^{-1}$ or $P_e P_t$.

Since not all Martian areas are equally likely to have detectable life forms, they noted that estimating the value of $P_e P_1$ requires trajectory information and the adequacy of the design of the experimental packages. Some representative numerical values of σ as a function of N and p are presented in Figure 1.

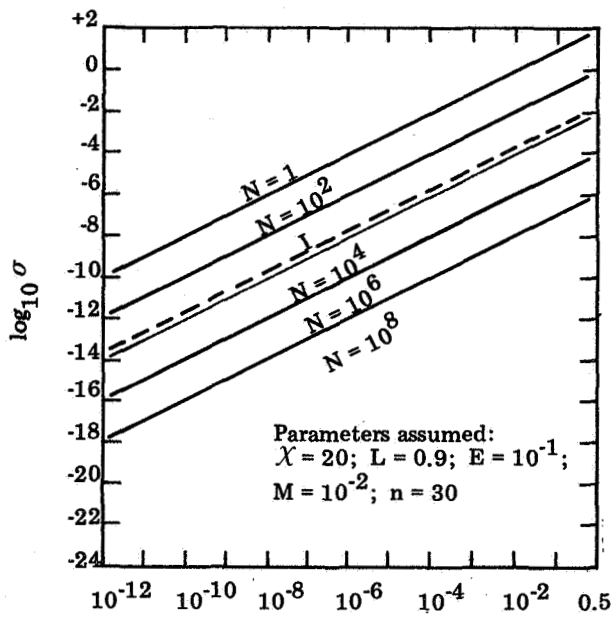


Figure 1 *Acceptable Risk of Planetary Contamination (after Sagan and Coleman, 1965, p. 24).*

The authors adopted $\simeq 10^{-1}$ as a preliminary value of the organisms surviving Martian conditions. However, they cautioned that the uncertainty involved is at least one order of magnitude. Therefore, they used $P_m \simeq 10^{-2}$. For these parameters, Figure 1 provides the minimum values of σ. By using equation (11) and Figure 1, σ can be redetermined with other parameters.

Sagan and Coleman suggested that there may be 60 possible Mars missions by the U.S. and U.S.S.R. before 1984, based on an average of three launches at each opportunity. Consequently, with $\chi \simeq 20$, there would be $N \simeq 1200$ possible experiments. They also assumed a number $n \simeq 30$ launches of flybys and orbiters as an upper limit. Within this context, the authors stated the following (Sagan and Coleman, 1965, p. 25):

> The existing sterilization requirements for Mars landing vehicles may be somewhat relaxed. For example, if we desire 99.9 percent probability that 1200 biological experiments can be performed before contamination, the mean number of viable micro-organisms deposited on the planet by each spacecraft may be as high as $\sigma \simeq 2 \times 10^{-4}$. When considering the conservative nature of the value of P_m, in particular, a value for the sterilization parameter σ in the range between 10^{-3} and 10^{-4} would seem quite adequate for an extensive program of biological exploration of Mars.

Similar values were proposed for the landing packages used for life detection.

It was also maintained by Sagan and Coleman that if a 99.9 percent probability of the landing program's being successfully completed prior to contamination by the accidental impact of a flyby or orbiter were desired, then the probability of accidental impact, based on equation (12), must be $P < 4 \times 10^{-5}$. Sagan and Coleman published a slightly revised version of this model in 1966, based on 100 missions rather than the 1000 used in the original work.

QUARANTINE STANDARDS

COSPAR Resolution 26.5, setting forth contamination probability standards and sterility requirements, was adopted at the 1964 COSPAR meeting in Florence, where the Sagan-Coleman paper was presented. Also known as the COSPAR Resolution of 1964, it was a response to the Sagan-Coleman study and to the report of the Consultative Group on Potentially Harmful Effects of Space Experiments, following the latter's 1964 Geneva meeting. At the meeting, it was suggested that only flyby missions be attempted in the exploration of Mars, at least at that time.

The Life Sciences Committee of the SSB held a conference on July 28, 1964, on the Hazard of Planetary Contamination Due to Microbiological Contamination in the Interior of Spacecraft Components. At this meeting, the COSPAR contamination probability standards set forth in Resolution 26.5 were fully endorsed. In addition, it was concluded that these standards should apply equally to the interiors of components.

According to Resolution 26.5, COSPAR accepted (COSPAR *Information Bulletin* No. 20, 1964, pp. 25–26)

> . . . as tentatively recommended interim objectives, a sterilization level such that the probability of a single viable organism aboard any spacecraft intended for planetary landing or atmospheric penetration would be less than 1×10^{-4}, and a probability limit for accidental planetary impact by unsterilized flyby or orbiting spacecraft of 3×10^{-5} or less.

Resolution 26.5 was a significant development, particularly in terms of NASA policy regarding sterility requirements. Hall and Lyle observed that the COSPAR Resolution of 1964 was (Hall and Lyle, 1971, p. 6) a

> . . . milestone in that for the first time, there was international agreement on quantitative objectives in terms of probabilities of events which characterize planetary contamination. An analytical rationale thus was provided for the recommended standards and the quarantine problem as it was understood at that time. Although particulars of the COSPAR Resolution of 1964 have been reconsidered in the light of increasing knowledge, it provided a framework which continues to serve in the development of quarantine standards. The essential elements of the framework are: (1) a model of the principal parameters and their interrelations; (2) agreements as to which parameters should serve as basic standards; and (3) assignment of quantitative values to the chosen parameters.

PROBABILITIES OF CONTAMINATION HAZARDS

In a critique of spacecraft sterilization standards, Schalkowsky (1966a) reviewed the Sagan and Coleman model and compared it with the COSPAR values. COSPAR used the analytical framework suggested by Sagan and Coleman, but adapted slightly different numerical values. Schalkowsky observed that Sagan and Coleman used σ to refer to the probability of an organism's being released on the surface of Mars, whereas the COSPAR value referred to the chance of a single organism's being aboard the lander. Schalkowsky correlated the relationship of the two as

$$\sigma = P_N \cdot P_R \tag{1}$$

where P_N is probability of one viable micro-organism aboard the lander and P_R is the mean probability that one micro-organism, if present, will be released from the lander and deposited on the Martian surface. He pointed out that the COSPAR and Sagan-Coleman definitions would be identical if P_R were assumed to be unity and showed that there is little numerical difference between the two:

	σ	P_i
COSPAR	1×10^{-4}	3.5×10^{-5}
Sagan and Coleman	$2 \times 10^{-4} (0.75 \times 10^{-4})$	$4 \times 10^{-5} (2 \times 10^{-5})$

Schalkowsky corrected the numbers in parentheses, with the difference due to the use by Sagan and Coleman of logarithms to the base 10 rather than what was called for by his own calculations.

Although he was not aware of an explicit statement from COSPAR regarding the values used for p, N, χ, P_m, P_e, P_l, P_t and n in arriving at the recommended values for σ and P_i, it can be inferred from the closeness to the Sagan and Coleman values of σ and P_i that approximately the same estimates were used.

Schalkowsky summarized the Sagan-Coleman analysis in the equation

$$\ln p^{-1} = \frac{\sigma N P_m}{\chi P_e \cdot P_t P_l} + nP_i \tag{2}$$

where

- p the probability that Mars will not be contaminated before N experiments are successfully completed
- σ the probability of one viable micro-organism on the surface of Mars due to a single lander
- N the desired number of successfully completed experiments in the unmanned Mars exploration program

P_m the probability that one organism deposited on the surface of Mars will survive, grow, and spread, thus leading to planetary contamination
χ the mean number of experiments per lander
P_e the mean probability that an experiment will work as designed
P_t the probability that the lander vehicle will perform its engineering functions after it is landed on the planetary surface
P_l the probability of finding experimental conditions on Mars (e.g., kind of life) compatible with experiment design
n the number of flybys and orbiters
P_i the probability of accidental impact by a flyby or orbiter

He rearranged this equation by replacing $\ln p^{-1}$ with p_c, the latter referring to the probability that the planet will be contaminated before N experiments are successfully completed. Schalkowsky continued the analysis with

$$p_c = 1 - p$$

and $$\ln p^{-1} = \ln \frac{1}{1-p_c} = -\ln (1-p_c) = p_c + \frac{1}{2}P_c^2 + \frac{1}{3}P_c^3 + \cdots$$

For small values of p_c, e.g., $p_c = 10^{-3}$,

$$\ln p^{-1} \approx p_c \tag{3}$$

Then M^L denotes the number of lander launches required to provide N successful experiments and R^L the mean probability that a launch will produce a successful Mars landing. Thus,

$$M^L \cdot R^L = \frac{N/\chi}{P_e \cdot P_t \cdot P_l} \tag{4}$$

By using equations (2), (3), and (4), equation (1) becomes

$$p_c = M^L \cdot R^L \cdot P_N \cdot P_R \cdot P_m + nP_i \tag{5}$$

Schalkowsky stated (Schalkowsky, 1966a, p. 5):

> If the analysis of probabilities of contamination is to have any practical significance, it is essential that P_N, the probability of a single viable micro-organism aboard a lander, be given a realistic meaning. To date, spacecraft sterilization practice has been based on the extrapolation of logarithmic kill rates due to dry heat, assuming a single species.

P_N is then derived from

$$P_N = N_o \cdot 10^{-t/D} \tag{6}$$

where

N_o initial population of micro-organisms on the lander (prior to the application of dry heat)

t length of time dry heat is applied at a particular fixed temperature

D time it takes to reduce a single-species population by a factor of 10 at a fixed temperature

He arrived at equation (7), the basis for evaluating contamination hazards, by combining equations (5) and (6), subject to the constraint imposed by $N_o \cdot 10^{-t/D} < 1$

$$p_c = M^L \cdot R^L \cdot N_o \cdot 10^{-t/D} \cdot P_R \cdot P_m + nP_i \tag{7}$$

Schalkowsky defined his approach to planetary contamination in terms of allocating risks between two independent events: (1) contamination as a result of a sterilized lander, $p_c(L)$, and (2) accidental impact by an unsterilized orbiter or flyby, $p_c(B)$. Therefore,

$$p_c = p_c(L) + p_c(B) \tag{8}$$

With the parameters used by Sagan and Coleman, equation (4), which denotes the number of Mars launches required for the desired number of successful experiments, leads to the following:

$$M^L \cdot R^L = \frac{N/X}{P_e \cdot P_t \cdot P_l} = \frac{1200/20}{(0.9)(0.1)} = 666$$

Then, if $R^L = 0.9$ is used as an average reliability value for successfully landing a spacecraft on Mars, the following result can be obtained:

$$M^L = \frac{666}{0.9} = 740$$

Schalkowsky considered this an unrealistic figure for the number of lander missions, i.e., it is too high for the 1-decade time period stated by COSPAR. Furthermore, it is not consistent with the Sagan and Coleman $n = 30$ figure for orbiters and flybys during the same period. He suggested that, as a first approximation, the number of orbiters and flybys should equal the number of landers. In other words, every lander will require a bus to bring it to the planet, and there is the possibility that the bus, which is unsterilized, will have an accidental impact on the planet. This difference, according to Schalkowsky, "casts some doubt as to

whether contamination hazards are suitably apportioned between $p_c(L)$ and $p_c(B)$" (Schalkowsky, 1966a, p. 7).

Using COSPAR values ($P_N = 10^{-4}$, $P_i = 3 \times 10^{-5}$) and equation (5), Schalkowsky calculated values similar to those above. He made no assumptions as to the desired number of successful experiments, but attempted to infer the values of M^L and n which would result if $p_c \approx 10^{-3}$, $p_r \approx 1$, and $P_m \approx 10^{-2}$. The second and third estimates are those used by Sagan and Coleman; they assume an equal distribution of hazards between $p_c(L)$ and $p_c(B)$:

$$M^L \cdot R^L \cdot P_N \cdot P_R \cdot P_m = nP_i = \tfrac{1}{2}p_c \tag{9}$$

With $R^L \approx 0.9$, the following is obtained:

$$M^L = \frac{(0.5)10^{-3}}{(0.9)10^{-4}10^{-2}} \approx 555$$

and

$$n = \frac{(0.5)10^{-3}}{3 \times 10^{-5}} \approx 17$$

Schalkowsky suggested that the inconsistency in the Sagan-Coleman analysis was carried over into the COSPAR values for P_N and P_i. In order to achieve better agreement between M^L and n, he assumed that $M^L \approx n \approx 30$ for the time period of one decade. More conservatively, $R^L \approx 1$, and the resulting values of P_N and P_i are

$$P_N = \frac{(0.5)10^{-3}}{(30)10^{-2}} \approx 2 \times 10^{-3}$$

$$P_i = \frac{(0.5)10^{-3}}{30} \approx 2 \times 10^{-5}$$

He concluded (Schalkowsky, 1966a, p. 8):

> The above calculations are intended to indicate that current standards may well have been based upon unrealistic estimates of the extent and nature of the Mars exploration program in the immediate future. It is, however, not intended to suggest that presently accepted standards be modified on the basis of the above alone. Indeed, it is the principal contention of this author that insofar as spacecraft sterilization is concerned, the formal adoption of any number for P_N without regard as to how it will be implemented, is of little practical value and should therefore not be done.

Sagan-Coleman Model A report prepared by the Sandia Corporation (1966) reviews some of the drawbacks in the Sagan-Coleman position.

It is noted that within the context of program development, the Sagan and Coleman paper was an effort to relate total planetary mission objectives to hardware requirements for planetary quarantine. Several objections to the model are described, such as the misunderstanding of the parameters used and the assumption that an infinite number of missions can be flown to achieve the overall objective of planetary exploration (Sandia Corporation, 1966, p. 7).

This latter assumption allows one to derive a requirement on σ, the expected number of micro-organisms per spacecraft upon impact with the planet, regardless of the probability of success of each of the flights, P_s. That is, while σ is a function of P_s, for any given P_s, it is possible to determine a value of σ which will allow the total exploration program's objectives to be met. This is not the case when some maximum, finite, number of flights is contemplated.

The Sagan-Coleman model has been modified to consider a finite number of flights and thereby remedy the last objection. Nevertheless, the Sandia report observes that without an additional analysis of the number of flights selected, the model is concerned only with sterilization objectives and not with exploration objectives. This is thought to be unreasonable because of the relationship between sterility requirements and reliability requirements when a finite number of missions is flown. It is this relationship which has not yet been thoroughly analyzed.

Ungar et al. (1966) consider the Sagan-Coleman model very comprehensive because it assumes values for a great number of eventualities. They found two of the parameters of special interest: "p," the probability that contamination with terrestrial micro-organisms does not occur until N experiments are performed;[1] and "P_-," the probability that a specific lander will contaminate Mars. The model states that $P_- \approx \sigma P_m$, with σ the mean number of micro-organisms deposited in a landing and P_m the probability that a specific organism deposited on the planet will multiply and contaminate a large fraction of its surface. The example used assumes that $P_m = 0.01$, and with 1200 experiments, the value of $\sigma \approx 2 \times 10^{-4}$, and, therefore, $P_- \approx 2 \times 10^{-6}$.

The formula is in error, according to Ungar et al., in that the 1200 experiments should be 1200 successful experiments and, thus, 12 000 flown experiments. Sagan and Coleman, in turn, acknowledged the error, but maintained that a compensating error left their final results unchanged.

Ungar et al. state (Ungar et al., 1966, p. 5):

The Sagan-Coleman model may not be used to compare the consequences of various potential Mars exploration profiles since the number of missions to be flown is not a parameter of the model. The number of biologically successful experiments is a parameter

[1] This is a large number and is assumed to be 0.999.

of the model. It was a confusion of these two parameters that lead to the erroneous substitution referred to above.

Two approaches by Sagan and Coleman to the contamination of Mars are discussed by Ungar et al. First, the model formulates the contamination probability for a series of experiments that are carried out until the desired data about Martian biology are obtained. Second, it provides an illustrative computation of the overall contamination probability necessary for such experiments by stating the equation in a way that includes an assumed value representing each parameter. However, since this is only one example, there is no demonstration of how the result would vary if other values were assumed. The authors present a new model based on an entirely different approach. The model and this new approach will be described later.

Cornell (1966a) considers the Sagan-Coleman analysis important, in that it provides a method of dealing quantitatively with the problems of spacecraft sterilization and probability levels for missions to Mars. Nevertheless, all mathematical models simplify reality, and he believes that this one does so, particularly in the light of the current state of knowledge. In other words, since little is known about the Martian surface or our engineering ability to solve many of the problems associated with missions to that planet, a complex model would not be practical (Cornell, 1966a, p. 3).

For instance, instead of dealing with mean probabilities such as P_+ and P_-, it would be better if enough was known so that underlying probability distribution could be incorporated into the model. Sagan and Coleman's model holds both P_+ P_- constant throughout the period of unmanned exploration of Mars. But P_+ is a function of our engineering ability and of selecting landing sites where profitable experimentation can be performed.

Cornell presents three reasons against taking a constant value for P_-. First, P_- represents the mean probability that a given lander will contaminate the Martian surface and, thus, P_- should be considerably greater for hard landings than for soft ones. The former would probably release more contaminants from fractured materials and the interior of the spacecraft. This risk can, of course, be reduced by lowering the chance of a hard landing and by decontaminating the interior of the ship. By modifying the Sagan-Coleman model to distinguish between the two types of landings, Cornell is able to show corresponding differences in the results. The modified model will be discussed below. His second point concerns the assumption by Sagan and Coleman of a constant probability that a spacecraft will be contaminated. The third factor relative to the constant value of P_- concerns the implication of a constant probability that a large area of Mars would be contaminated by a viable organism deposited on its surface. This probability would, however, change as the impact area changes.

Proposed Alterations to Standards A paper by Hall (1964) was one of those dealing with contamination risk and probability considered in the formulation of NASA policy. Hall describes a mathematical model which suggests that the standards stated in COSPAR Resolution 26.5 could be lowered by one or two orders of magnitude. The basic premise of this model is that the "level of commitment" will be about 99.9 percent; i.e., that there will be 99.9 percent confidence that a planet will not be contaminated with terrestrial micro-organisms in this period (1966–1985) during which 100 missions might be launched and biological experiments performed.

The model uses the following designations (Hall, 1964, Appendix A): where

- P the probability of contamination in the total program
- Q the probability of no contamination in the total program
- P_i the probability of contamination on the *nth* flight
- n the number of missions
- P_r the probability of the release of a viable organism on the planet
- $P_{g.s.}$ the probability of the survival, growth, and spreading of a single organism on the planetary surface
- P_a the probability of an accidental impact of an unsterile vehicle

Within the total program, the contamination probability is then given as

$$P=l-Q=l-\frac{n}{i=l}(l-P_i)$$

Where the P_i are quite small, their products are negligible, and

$$P=\frac{n}{i=l}P_i$$

If all of the P_i are equal, then

$$P=nP_i$$

With a 99.9 percent confidence standard that a planet will not be contaminated by unmanned missions, P is defined as equal to 1.0×10^{-3}. Thus, after solving for P_i, $P_i=\frac{P}{n}=\frac{1.0\times10^{-3}}{100}=1\times10^{-5}$, there is, for each mission, a 1×10^{-5} probability of contamination of a single terrestrial micro-organism.

Since not every micro-organism deposited on a planet's surface will survive, grow, and spread, it is assumed that there is a 10^{-3} probability

for such an event. Therefore, the chance that a single viable microorganism will be released is

$$\frac{P_r = P_i}{P_{g \cdot s \cdot}} = \frac{1 \times 10^{-5}}{10^{-3}} = 1 \times 10^{-2}$$

Consequently, there is less than a 1×10^{-2} chance that a viable microorganism will be released among those modes of contamination in which this might occur. That is, the mean number of viable organisms released by each vehicle should be 1×10^{-2}.

The 1×10^{-2} probability does not apply to all modes, however. For example, an unsterile vehicle with a large population of heterogeneous organisms requires a different approach. It is assumed that the contamination probability for such a vehicle would not be greater than 1×10^{-5}, the value for other sources in a given mission. A conservative estimate of the chance of contamination after an accidental impact is given as 10^{-1}, and solving for the probability of accidental impact:

$$P_a = \frac{1 \times 10^{-5}}{10^{-1}} = 1 \times 10^{-4}$$

PLANETARY CONTAMINATION MODELS

The Sixth International Space Symposium held in Mar del Plata, Argentina, May 11–19, 1965, was sponsored in part by COSPAR and the ICSU. Prior to the meeting, an unsuccessful attempt was made to organize an international conference on biological exploration sterilization and techniques. Nevertheless, a Panel on Standards for Space Probe Sterilization had been established by the Consultative Group on Potentially Harmful Effects of Space Experiments, and a special session was held. Two of the papers presented concerned new developments and implementation of sterilization techniques (Davis and Horowitz, 1966; Nicks and Miles, 1966).

At about the same time, Geiger et al. (1965) published a paper discussing sterilization probabilities in relation to Mars, Venus, the Moon, Mercury, and the Jovian planets. In it, the authors suggest one way to provide reasonable assurance that contamination not occur on Mars: keep the probability of contaminating the planet to a level equal to the chance that no significant biological evidence would be acquired for all other reasons combined. They assume that seven oppositions to Mars would permit 14 to 28 flights, with a 1 to 2 chance of reaching the planet each time. The probability of failure due to engineering or technical problems is estimated at 3 to 4, thus making the chance of not obtaining data concerning the presence of life on any one attempt 7 to 8. In a series of 28 attempts, the probability of not acquiring such data would then be 7 to 8 or 10^{-2}. Therefore, they recommend that the chance of contaminating the planet during the entire program be kept as low as 10^{-2}. In contrast, Sagan and Coleman "would require all these missions to be successful before the planet is considered to be contaminated with the above degree of confidence" (Geiger et al., 1965, p. 311).

An alternative estimate of the chance of contaminating Mars would be to keep the probability low during unmanned missions relative to the probability during the first manned landing. During a manned mission, contamination to some degree would be likely, with a chance of 10^{-1} or higher. Therefore, 10^{-2} is suggested as a reasonably small probability for contamination for all of the unmanned flights.

Geiger et al. believe that 10^{-2} for the number of flights (14) that actually reach Mars indicates a maximum contamination probability on each of the flights of 10^{-3}, with 10^{-4} per flight a reasonable and conservative level. This is the same value suggested by Hobby (cited in Geiger et al., 1965), by the SSB, and at the 1964 COSPAR meeting in Florence.

Venus does not require the same contamination probability, according to Geiger et al., because of the hostility of the environment to terrestrial organisms. In other words, its surface temperature is much too high, although there are cool regions in its upper atmosphere. However, these authors point out that micro-organisms apparently would not multiply under such conditions, and the chance for the growth of terrestrial organisms on Venus is estimated at 10^{-3}. Therefore, by dividing 10^{-4} per flight by 10^{-3}, 10^{-1} is obtained as the assurance against the release of terrestrial organisms into Venus' upper atmosphere.

The sterility of spacecraft in missions to the Moon is not considered essential by the authors. They note that although Sagan and Imshenetsky believe there is a remote chance for growth, this view is not accepted by others. Nevertheless, Geiger et al. agree that it would be highly desirable to prevent contamination of the Moon. With a surface area of 4×10^7 cm^2 (Geiger et al., 1965, p. 313),

> . . . the chances of picking up terrestrial organisms within this area should be low, compared to the other chances of contamination or error in a single experiment, approximately 10^{-3}. Accordingly, the probability that an Earth organism is found on the lunar surface should be held to 10^{-6} per $cm.^2$. For the entire Moon, then, it should be undesirable to put down more than 4×10^{11} organisms from all unmanned flights. For a 40-flight, unmanned program, this would mean an average of less than 10^{10} organisms per flight.

Mercury does not present the same contamination problems because it has very high temperatures on one face and low temperatures on the opposite face. Although there might be a narrow bond between the bright and dark regions more hospitable to terrestrial organisms, the lack of moisture and a suitable atmosphere leads to the conclusion that it is not necessary to consider Mercury as a contamination problem.

Geiger et al. maintain that exploration of the Jovian planets might be carried out initially under the same restrictions discussed for Mars. Clemedson (1964) suggests that Jupiter is the next logical target after Mars, but he does not believe that there is much chance that terrestrial organisms could survive and multiply on Jupiter or the other outer planets. He does observe that R. L. Forward (1962; cited in Clemedson, 1964) reported the results of experiments in which a simulated Jovian atmosphere was exposed to ultraviolet radiation, resulting in the formation of a number of simple organic compounds.

During 1966, a number of papers and reports appeared outlining new planetary contamination models and positions on various aspects of

the problem. Some of these works have already been discussed. At the COSPAR meeting in Vienna in 1966, the chairman of the Consultative Group on the Potentially Harmful Effects of Space Experiments, with the advice of the Panel of Standards of Space Probe Sterilization, made a number of recommendations. COSPAR Resolution 26.5 was reviewed, and it was suggested that the probability of a single viable organism aboard a spacecraft should be less than 1×10^{-4}, and that the chance for accidental impact by unsterilized flyby or orbiting space ships should be 3×10^{-5} or less. The chairman stated that the 1×10^{-3} probability (i.e., one chance in a thousand) of contaminating a planet during the entire period of biological exploration, which was the basis for the mathematical model used for the COSPAR objectives stated in Resolution 26.5, was still a reasonable overall objective.

However, because of errors and hazards not considered in the original model, many problems were encountered when attempts were made to reduce this objective to specific categories of contamination probabilities for landers and unsterilized flybys. In addition, spacecraft design and operations were unnecessarily restricted when specific parts of the probability objective were applied to each of the hazards. Nevertheless, it was proposed that the 1×10^{-3} probability of contaminating a planet be continued as the criterion for the exploration of Mars and other planets. It was also stated that the mathematical model to be used in the combination of probabilities for individual factors should be conservative, and that there should be a probability of not less than 10^{-3} that micro-organisms subjected to a sterilization procedure would grow and spread after landing on a planet's surface. The latter value was changed from the 10^{-2} probability inferred from the 1964 COSPAR model, but it was not designed to be adopted into the overall probability until there was agreement about the general formation. The comparable standard for organisms not exposed to sterilization procedures was to be taken as unity.

DETERMINATION OF PARAMETERS

Ungar et al. (1966) of the ITT Research Institute, formulated a contamination model which is regarded as an alternative to, but not a replacement for, the Sagan-Coleman model. It is based on an assumed mission profile of a Mars flight, with a range of probabilities calculated for each event in the mission and a parametrically derived contamination probability for the entire mission. The authors make it clear that if the spaceship is properly sterilized the probability that a specific event will result in the contamination of Mars will not be a function of the values that were used in the model's definition of contamination. Instead, these event probabilities are seen as dependent on engineering, physical, and biological factors.

A sensitivity analysis on each of the parameters was carried out by the authors; the contamination probability for each mission was used to obtain the overall probability for a series of N missions. The assumptions underlying the approach were as follows:

1. Rather than taking into account the success or failure of the mission, two values were assumed for the number of missions in the program (10 and 25).
2. The mission profile was adapted from a *Saturn V* Voyager mission described by Craven et al. (1966).
3. Rather than define the term "contamination," a range of values was assumed for each model parameter, with the expectation that those values which will eventually be thought to constitute contamination will be found in this range.

Each possible event in the mission is listed in Table 2, and is represented by a symbol in the left-hand column. A symbol with a bar above it denotes a negative, i.e., T is the probability of a successful transit trajectory, where $\bar{T}$ is the probability of failure.

The symbol q stands for the probability that a single launch will produce no contamination and, on the basis of the events in the mission, the authors derive the following equation:

$$q = T(E\bar{c}_1 + \bar{E})(I\bar{c}_2 + \bar{I})\{M(D\bar{c}_7 + \bar{D})[L(\bar{R}[S\bar{c}_3 + \bar{S}\bar{c}_4] + R[S\bar{c}_5 + \bar{S}\bar{c}_6]) + \bar{L}] + \bar{M}\bar{c}_8\}^2 + \bar{T}$$

Where there is a total of N missions, the overall probability of no resulting contamination is thus $Q = q^N$, and the overall probability of contamination produced by N missions is $P = (1 - Q)$.

To compute the values of P, the overall probability of contamination in N launches, 576 sets of parametric values were used. These sets were obtained with the use of the following parameters and values (the ranges were obtained from JPL):

Parameter:	T	M	L	R	S	$(\bar{c}_3, \bar{c}_4)$	$\bar{c}_6$	N
Number of values:	$2 \times$	$2 \times$	$2 \times$	$2 \times$	$2 \times$	$\times$	$\times$	$\times 2 = 576$

Ungar et al. state (Ungar et al., 1966, p. 12):

> The results were examined with particular attention to N, the number of launches, and $\bar{c}_6$, the probability of no contamination associated with the events "recontamination of the capsule and a hard landing."
>
> It is obvious that the higher the probability of landing a capsule, all other facts being equal, the higher the probability of contamination. This effect involves the parameters T,

M, and L (among those for which more than one value was used). Given a landing, both recontamination (R) and a *hard* landing ($\bar{S}$) increase the probability of contamination.

With these gross effects in mind, for fixed N and $\bar{c}_6$, the least chance of contamination occurs when T, M, L, and R are at their smaller values, and S, $\bar{c}_3$ and $\bar{c}_4$ are at their smallest values.

Table 2 *Definition of Events in Mission Profile (after Ungar et al., 1966, p. 10).*

Symbol	Description
T	Achievement of transit trajectory
I	Injection stage impacts
E	Impact on Mars of ejecta and efflux cloud and/or micrometeorite spalling from spacecraft in Mars orbit. Includes both vehicles
M_i	Successful Mars orbit of i^{th} vehicle(1)
L_i	Separation and impact of i^{th} capsule on Mars(1)
S_i	Soft landing of i^{th} capsule[on Mars](1)
R_i	Recontamination occurring when biological barrier on i^{th} sterilized capsule separates(1)
D_i	Decay of orbit of i^{th} spacecraft resulting in impact on Mars(1)
c_1	Contamination from ejecta flux
c_2	Contamination from impact of injection stage
c_3	Contamination from soft landing of capsule
c_4	Contamination from hard landing of capsule
c_5	Contamination from soft landing of recontaminated capsule
c_6	Contamination from hard landing of recontaminated capsule
c_7	Contamination from orbital decay of spacecraft
c_8	Contamination from failure to achieve orbit

(1)The subscripts are dropped in the contamination equation because identical event probabilities are assumed for each spacecraft.

Table 3 shows the range of values for each parameter and the sensitivity of the contamination equation variations within these ranges. The authors then present the effects of four combinations of values for N and $\bar{c}_6$. For Case 1, $N=10$, $\bar{c}_6=0.5$; Case 2, $N=10$, $\bar{c}_6=0.99$; Case 3, $N=25$, $\bar{c}_6=0.90$; Case 4, $N=25$, $\bar{c}_6=0.99$.

Case 1: $N=10$, $\bar{c}_6=0.5$

1.1 *Favorable conditions* (T, M, L, R small; S, $\bar{c}_3$, $\bar{c}_4$ large). The overall probability of contamination, P, equals 4×10^{-4} and is insensitive to changes in T, M, or L. The following points are pertinent:

a. P increases from 4×10^{-4} to 7.8×10^{-3}, as R (recontamination probability) increases from 10^{-4} to 10^{-2}.
b. P increases from 4×10^{-4} to 7×10^{-4}, as S (soft landing probability) is decreased over the range 0.9 to 0.75.
c. P increases from 4×10^{-4} to 2.9×10^{-3}, as $\bar{c}_3$ and $\bar{c}_4$ decrease

from 0.99999 to 0.9999 and 0.9999 to 0.999, respectively.

1.2 *Unfavorable conditions* (T, M, L, R large; S, $\bar{c}_3$, $\bar{c}_4$ small). The overall probability of contamination, P, equals 2.6×10^{-2} and is insensitive to changes in T, M, L, $\bar{c}_3$, or $\bar{c}_4$. The following points are pertinent:

a. P decreases from 2.6×10^{-2} to 5.6×10^{-3}, as R (recontamination probability) decreases from 10^{-2} to 10^{-4}.

b. P decreases from 2.6×10^{-2} to 1.3×10^{-2}, as S (soft landing probability) increases from 0.75 to 0.9.

Table 3 *Range of Probability Values for Each Parameter and the Sensitivity of the Contamination Equation to Them (after Ungar et al., 1966, p. 14.).*

Parameter	Probability Values Used in Computation	Relative Sensitivity
T	0.90; 0.95	Insensitive
M	0.80; 0.90	Insensitive
L	0.950; 0.975	Insensitive
R	1×10^{-4}; 1×10^{-2}	Sensitive
S	0.75; 0.90	Fairly sensitive
N	10; 25	Fairly sensitive
I	5×10^{-3}	–
E	1×10^{-3}	–
D	5×10^{-4}	–
$\bar{c}_3$	0.999; 0.9999; 0.99999	Sensitive
$\bar{c}_4$	0.999; 0.999; 0.9999	
$\bar{c}_6$	0.50; 0.90; 0.99	Insensitive
$\bar{c}_1$	0.999999	–
$\bar{c}_2$	0.999999	–
$\bar{c}_5$	0.999	–
$\bar{c}_7$	0.999999	–
$\bar{c}_8$	0.99999	–

Case 2: $N = 10$, $\bar{c}_6 = 0.99$

2.1 *Favorable conditions.* The overall probability of contamination, P, equals 3×10^{-4}, and all effects are approximately as in 1.1 above.

2.2 *Unfavorable conditions.* The overall probability of contamination, P, equals 5.9×10^{-3} and is insensitive to changes in T, M, L, or R. The following points are pertinent:

a. P decreases from 5.9×10^{-3} to 3.5×10^{-3}, as S (soft landing probability) increases from 0.75 to 0.9.

b. P decreases from 5.9×10^{-3} to 1.1×10^{-3}, as $\bar{c}_3$ and $\bar{c}_4$ increase by an order of magnitude.

Case 3: $N = 25$, $\bar{c}_6 = 0.90$

3.1 *Favorable conditions.* The overall probability of contamination, P, equals 3×10^{-4}, and all effects are approximately as in 1.1 above. following points are pertinent:

a. P increases from 8×10^{-4} to 4.5×10^{-3}, as R increases from 10^{-4} to 10^{-2}.
b. P increases from 8×10^{-4} to 1.3×10^{-3}, as S decreases from 0.9 to 0.75.
c. P increases from 8×10^{-4} to 6.6×10^{-3}, as $\bar{c}_3$ and $\bar{c}_4$ decrease by an order of magnitude.

3.2 *Unfavorable conditions.* The overall probability of contamination, P, equals 2.4×10^{-2} and is insensitive to changes in T, M, or L. P decreases from 2.4×10^{-2} to 1.2×10^{-2}, as R decreases and S and $\bar{c}_4$ increase over their respective ranges.

Case 4: $N = 25$, $\bar{c}_6 = 0.99$

4.1 *Favorable conditions.* The overall probability of contamination, P, equals 7×10^{-4}, and all effects are approximately as in 3.1 above.

4.2 *Unfavorable conditions.* The overall probability of contamination, P, equals 1.47×10^{-2} and is insensitive to changes in T, M, L, or R. The following points are pertinent:

a. P decreases from 1.47×10^{-2} to 8.6×10^{-2}, as S increases from 0.75 to 0.9.
b. P decreases from 1.47×10^{-2} to 2.7×10^{-3}, as $\bar{c}_3$ and $\bar{c}_4$ increase by an order of magnitude.

Table 4 presents the ranges of the described values of the overall contamination probability (P) for the four cases shown above. Table 5 indicates the contamination probability per launch ($1-q$).

Table 4 *Range of Values for Overall Contamination Probability (after Ungar et al., 1966, p. 18).*

Number of Missions N	$\bar{c}_6$	Derived Values of P	
		Favorable Conditions	Unfavorable Conditions
10	0.50	4×10^{-4}	2.6×10^{-2}
10	0.99	3×10^{-4}	5.9×10^{-3}
25	0.90	8×10^{-4}	2.4×10^{-2}
25	0.99	7×10^{-4}	1.5×10^{-2}

Cornell (1966a) presents a model unlike that of Sagan and Coleman, in that it differentiates between hard and soft landings and the probability of

each one's leading to contamination. He defines several mean probabilities [1] which are considered constants. Cornell designates P_s as the probability of a soft landing, p_i as the probability of event E_i ; E_1 as a soft landing followed by successful biological experiments; E_2 as a soft landing without successful experiments; and E_3 as a hard landing with either no experiments or unsuccessful experiments.

Table 5 *Range of Values for Contamination Probability per Launch (after Ungar et al., 1966, p. 18).*

$\bar{c}_6$	Derived Values of $1-q$	
	Favorable Conditions	Unfavorable Conditions
0.99	3×10^{-5}	6×10^{-4}
0.90	3×10^{-5}	1×10^{-3}
0.50	4×10^{-5}	2.6×10^{-3}

He assumes that $p_1+p_2+p_3=1$, i.e., no hard landing will be followed by a successful experiment, and states that $p_1=P_+ P_s$, $p_2=(1-P_+)P_s$, and $p_3=1-P_s$.

Within the context of the Sagan-Coleman analysis, Cornell assumes further that all of the missions are independent of the others in terms of their results, so that the probability of N successful missions on $(N+m)$ attempts can be written as

$$\binom{N+m-1}{N-1} p_1^N (p_2+p_3)^m$$

where

$$\binom{N+m-1}{N-1}=\frac{(N+m-1)!}{(N-1)!m!}$$

When there are no failures, Cornell states the probability that j of these occur after soft landings and that $(m-j)$ as the result of hard landings is

$$\binom{m}{j}\left(\frac{p_2}{p_2+p_3}\right)^j\left(\frac{p_3}{p_2+p_3}\right)^k$$

[1] According to Cornell, mean probabilities are those which will change during a period of time.

He assumes that the probability that event E_i contaminates Mars is u_i for $i = 1, 2$, or 3. Then, the probability of NE_1 events, jE_2 events, and $(m-j)E_3$ events with no contamination is

$$\binom{N+m-1}{N-1} p_1^N (p_2+p_3)^m \binom{m}{j} \left(\frac{p_2}{p_3+p_3}\right)^j \left(\frac{p_3}{p_2+p_3}\right)^{m-j} (1-u_1)^N (1-u_2)^j (1-u_3)^{m-j}$$

Cornell then simplifies and sums over the complete j and m ranges, so that the probability of completing N successful biological missions with no contamination of Mars is

$$p = q_1^N [1 - (q_2 + q_3)]^{-N}$$

where

$$q_i = p_i(1 - u_i),\ i = 1, 2, \text{ or } 3 \tag{1}$$

He then takes

$$u = u_1 = u_2 = u_3/K \tag{2}$$

with $K \geqslant 1$. Cornell points out that Sagan and Coleman considered an example in which $K=1$, giving $u=P_-$. He substitutes the values from equation (2) in equation (1) and, since $p_1 + p_2 + p_3 = 1$, he obtains the following:

$$p^{1/N} = \frac{p_1^{(1-u)}}{1 - (1-p_1)(1-u) + p_3(K-1)u} \tag{3}$$

Like Sagan and Coleman, Cornell disregards second order and higher terms in $(1_{np})/N$ and μ, designating $p^{1/N}=1+(1_{np})/N$ and substituting in equation (2) to get

$$\ln p^{-1} = Nu[1+p_3(K-1)]/p_1 \tag{4}$$

However, when $P_-(K)$ is the probability that a lander will contaminate Mars under equation (2),

$$P_-(K) = \sum_{i=1}^{3} p_1 u_i = u[1+p_3(K-1)] \tag{5}$$

When $K=1$, this equals $u=P_-$. Taking equation (5), Cornell is able to solve (4), giving

$$P_-(K) = p_1 \ln p^{-1}/N \tag{6}$$

If p, N, and p_1 are all specified in Cornell's model, then $P_-(K)$ has to be less than the constant obtained by substituting p, N, and p_1 in equation (6) to meet sterilization requirements. However, he states that in equation (5) $P_-(K)$ is a monotonic increasing function of K.

If it is agreed that K should be taken to be greater than 1, rather than equal to 1 as in the Sagan-Coleman studies, then in order for $P_-(K)$ to meet decontamination requirements for given p_3, the permissible upper bound on u would have to be reduced accordingly. For instance, if C equals the upper bound allowable for $P_-(K)$ determined by substitution in (6), then an upper bound on u, derived from (5) is

$$u < C/[1+p_3(K-1)] \tag{7}$$

Cornell discusses an example of his approach by using $p_1=0.09$, $N=60$, and $p=0.999$, the values proposed by Sagan and Coleman, with N as the number of successful flights rather than the number of successful experiments. They estimated that the latter would be approximately 20 times as great, assuming that all experiments in a given flight would be equally successful. Using equation (5), and substituting, gives $C=(0.09)\ (0.001)/60=1.5\times10^{-6}$. Therefore, when $K=1$, $u=P_-$ would have to be less than 1.5×10^{-6}, and the corresponding figure for σ would be 1.5×10^{-4}, when P_m is 0.01.

The parameters described above are those which Sagan and Coleman used to arrive at their 10^{-4} probability that a spacecraft for a Mars landing is nonsterile (σ). The model Cornell suggests has somewhat higher standards, but he also presents a model that is not as stringent as that of Sagan and Coleman. He notes that the Sagan-Coleman analysis derived the expression

$$\sigma=\frac{P_+}{P_mN}\ln p^{-1} \tag{8}$$

from the equation

$$p=\left[\frac{P_+(1-P_-)}{1-(1-P_+)(1-P_-)}\right]^N \tag{9}$$

This is equivalent to Cornell's equation (6), since $K=1$. Then, $P_-(K)=P_-=\sigma P_m$, and $p_1=P_+$. It was stated earlier that when $P_+=0.09$, $N=60$, $p=0.999$, and $P_m=0.01$. Then, $\sigma=1.5\times10^{-4}$.

Cornell discusses the parameters on the right side of equation (8), in which $P_m=0.01$ was used. P_m is the probability of a single terrestrial organism's contaminating a large area of the Martian surface. Thus, the value selected for P_m would depend on the size of the area and the ability

of the organisms to survive in the Martian environment. As more evidence is obtained from Martian explorations, the values of P_m will have a more objective basis, and will probably decrease slowly. Cornell considers P_+, the probability of success for a lander, within the same context because of the lack of precise information. He expects P_+ to increase as more is learned about the Martian surface.

Cornell observes that since p is the probability of N biologically successful missions, the two parameters (p and N) are closely related, although the strength of the relationship (the specification of p) is arbitrary. Sagan and Coleman designated $p = 0.999$, making $1_{np}{}^{-1} = 0.001$. They also took N (or N/χ as they stated) as 60, whereas Jaffe designated it as 28. However, Cornell does not believe it is reasonable for them to have taken N as the total number of missions anticipated prior to manned missions to the planet, since it would be expected that the parameters would change. In addition, using the maximum value of N does not allow for unsuccessful missions. Cornell believes that it would be better to take a small value for N, giving a high probability of noncontamination while the first few successful biological missions are completed (Cornell, 1966a, p. 11).

In other words, the presently low value of 10^{-4} required for σ is to some extent low because a large value of N is considered. Thus the decontamination standards are somewhat based on the number of missions which are possible from an engineering viewpoint, not the number which are desirable based on current biological knowledge. The approach suggested here would correct this.

Using equation (8), Cornell adopts $N = 5$, keeping $P_m = 0.01$ and $P_+ = 0.09$. Without regard to flybys, σ becomes equal to 1.8×10^{-3}, 12 times larger than the probability calculated with the parameters used by Sagan and Coleman.

NOMENCLATURE OF SYMBOLS

Cornell (1966b) has also developed *A Nomenclature of Symbols Relevant to the Probability of Contamination of Mars*. It is similar to one developed earlier by Schalkowsky and Cooley (1966), which presented an analytical model detailing the relationship between planetary quarantine requirements and estimated probabilities of contamination. The nomenclature and symbol categories were defined as

P	the probability of planetary contamination
p	the event probability which is a component of a planetary contamination probability (P)
Prime superscripts	probabilities relating to unsterilized organisms; the absence of a prime thus denotes probabilities relating to organisms that have undergone sterilization
n_L	the number of lander vehicles launched over the time period under consideration. These landers will

be sterilized in their entirety prior to their launch

n_U the number of unsterilized buses, orbiters, and flybys launched over the time period under consideration

P the probability that any one landing vehicle, i.e., any one of the n_L's, will contaminate the planet or its atmosphere

P' the probability that any one of the unsterilized buses, orbiters, or flybys, i.e., any one of the n_U's will contaminate the planet or its atmosphere

P_c the probability that the planet will be contaminated during the time period under consideration

p_P the probability that one viable organism in a lander previously subjected to heat sterilization will be present on the planet's surface or in its atmosphere

p'_P the probability that one or more viable organisms not previously heat sterilized will be present on the planet's surface or in its atmosphere

p_G the probability that a viable, but previously heat sterilized, organism present on the planet's surface will grow and spread so as to contaminate the planet or its atmosphere

p'_G the probability that the one or more viable organisms that have not been previously heat sterilized and are present on the planet's surface or in its atmosphere will grow and spread and contaminate the planet or its atmosphere

p_N the probability that one organism in a lander vehicle will remain viable after heat sterilization and transit to the planet

p_R the probability that a viable organism if present in a sterilized lander will be released onto the planet's surface

N the number of viable organisms in a lander after heat sterilization

N_o the number of viable organisms in a lander prior to heat sterilization

t the heat sterilization time

D the time to reduce population of viable organisms by a factor of 10 at the selected sterilization temperature

N'_o the number of viable organisms on an unsterilized spacecraft, or portions thereof, at the time it

reaches a position to become a contamination hazard

N' the number of viable organisms from an unsterilized spacecraft which are deposited on the planet's surface or in its atmosphere

p'_T the probability that one or more viable, but previously unsterilized, organisms will be transferred from a bus, orbiter, or flyby to the planet or its atmosphere

p'_R the probability that viable, but previously unsterilized, organisms transferred to the planet will be released onto the planet's surface or into its atmosphere

p'_N the probability of one viable organism not previously heat sterilized on that planet's surface or in its atmosphere

Note: N and p_N refer to organisms on a lander prior to release (with probability p_R) onto the planet's surface or its atmosphere. However, N' and p'_N refer to organisms after release (with probability p'_R) onto the planet's surface or into its atmosphere.

The authors base their analysis on the following propositions: (1) planetary contamination probabilities resulting from a given spaceship will be considerably less than 1 and (2) during the period of time involved, these will be constant probabilities for all cases in any one category. They state further that

$$P_c = n_L P + n_U P' \tag{1}$$

P and P' are defined as

$$P = p_P \cdot p_G \tag{2}$$

$$P' = \sum^{i} (p'_P \cdot p'_G)_i \tag{3}$$

They write equation (3) as the sum of i terms in order to take into account the different sources of contamination such as accidental impact of an unsterilized ship, ejecta and emissions from such a craft, and recontamination of a sterilized lander.

After specific values for P_c, n_L, n_U, p_G, and p'_G are accepted, p_P and p'_P, become the design criteria for landers and unsterilized ships. These criteria are defined as consisting of the following probabilities:

$$p_P = p_N \cdot p_R \tag{4}$$

$$p'_P = p'_T \cdot p'_R \tag{5}$$

These are operational equations, with the terms on the right side representing, for example, best cycle specifications (p_N).

CALCULATIONS OF CONTAMINATION PROBABILITIES

Schalkowsky and Cooley (1966) believe that perhaps all of the analyses of planetary contamination probabilities calculated prior to this one, including that of Sagan and Coleman, can be reduced to the terms outlined above without any loss of accuracy.

They define the complete equation for planetary contamination probability as

$$P_c = n_L p_N p_R p_G + n_U \sum^{i} (p'_T p'_R p'_G)_i \tag{6}$$

- n_L — number of landers
- p_N — probability of one organism in lander
- p_R — probability of release from lander
- p_G — probability of growth and spreading
- n_U — number of unsterilized vehicles
- p'_T — probability of transfer to planet
- p'_R — probability of release on planet
- p'_G — probability of growth and spreading

With reference to equation (1), the authors use the following values for P_c, n_L, and n_U in establishing a standard for preventing contamination of Mars:

$$P_c < 10^{-3}; n_L = 70; n_U = 30$$

Thus, there would be less than 1/1 000 probability of contamination for 100 Mars launchings (Schalkowsky and Cooley, 1966, p. 6).

The division of the total number of vehicles into 70 landers and 30 unsterilized buses, orbiters, and flybys does not define a unique division of the total allowable contamination probability of $P_c < 10^{-3}$ between P and P'. Specific choices of P and P' are properly left as system tradeoff parameters. However, the selection of n_L and n_U places an upper limit on P and P'. For, clearly, P or P' cannot be chosen to be less than zero. Therefore, $P' < 3.33 \times 10^{-5}$ and $P < 1.43 \times 10^{-5}$.

They also give specific values to p_G and $p'_G : p_G = 10^{-3}$, which shows the probability of growth and spreading due to one viable terrestrial micro-organism previously subjected to heat sterilization.

When unsterilized vehicles are considered, p'_P is defined as the probability of "one or more" micro-organisms on the Martian surface, in order to take into account the different sources of contamination. As a result, the authors consider it necessary to also relate p'_G to the number of viable but unsterilized micro-organisms released on the planet or in its atmosphere in any of the i events. The values used are

when $N' \geq 100$, $p'_G = 1$
when $1 \leq N' < 100$, $p'_G = N' \cdot 10^{-2}$
when $N' < 1$, $p'_G = p_N \cdot 10^{-2}$

In the case of a calculation producing $N' < 1$, N' is taken to be equal to the chance of having a single viable surviving micro-organism.

The chance of growth and spreading is considered unity when 100 or more viable micro-organisms are considered; whereas, when small numbers are involved, the approach is in terms of one survivor. Therefore, when $N' = 1$, the authors adopt a value of $p'_G = 10^{-2}$, which is greater than p_G by one order of magnitude.

The values of p_p and p'_p are restricted by the choice of parameters. The probabilities of release, p_R and p'_R, would initially be taken to be unity, although it might be shown that they are less than unity. They are regarded in part of the implementation process with p_N and p'_T. With these values described above, Schalkowsky and Cooley define planetary contamination requirements in the following equations.

1. Planetary contamination probabilities—equation (1):

$$70P + 30P' \leq 10^{-3}$$

or

$$0.7P + 0.3P' \leq 10^{-5} \tag{7}$$

2. Sterilized landers—equation (2):

$$P = 10^{-3} P_P$$

or

$$p_P = 10^3 P \tag{8}$$

They state that P cannot be greater than 1.43×10^{-5} regardless of the value assigned to P and P'_{-2}. The value will depend on various mission design considerations.

3. Unsterilized vehicles—equation (3): A simple statement regarding unsterilized organisms cannot be given, because it is necessary to take into account the various modes of contamination. It must be stated in the form of equation (3) and its values of p'. However, P' will be less than 3.33×10^{-5}, depending on P and P'.

COMPARISON OF MODELS

The Schalkowsky and Cooley comparison of planetary quarantine models is presented in Table 6. It shows (Schalkowsky and Cooley, 1966, p. 9)

> . . . resulting values of the various parameters for two cases using the present model. Case (a) (item 4 of Table 6) assumes the same distributions between P and P' that were used in items 1, 2, and 3. Case (b) (item 5) shows a distribution which favors unsterilized vehicles by a factor of 31. Data for the Sagan and Coleman analysis (item 1) have been taken from the article published in the May 1965 issue of *Aeronautics and Astronautics* (p. 22). Item (2) of Table 6 represents a correction in the Sagan and Coleman data stemming from a minor error in their numerical calculations. Regarding the COSPAR values, only p_N and p'_T are formally provided in COSPAR resolutions. The other values in item 3 are therefore inferred on the assumption that they have been derived from the Sagan-Coleman analysis.

Sherry and Trauth developed a model (Sherry and Trauth, 1966, p. 1)

> . . . which relates general planetary exploration objectives to spacecraft-oriented planetary quarantine requirements (sterility levels). This model is somewhat more realistic than (some) previous models in that it considers only a finite number of missions. When only finitely many missions are envisioned, the probability that a mission contaminates the planet is highly dependent upon the probability of mission success. So much so, in fact, that for certain (not unreasonable) parameter values, it is impossible to obtain a sterility level. In many other cases, even when a level can be obtained, it is impracticably severe. This suggests that further investigation will be needed before agreement is reached about spacecraft sterility levels.

Mission Probabilities—Success or Failure The probability (P) that a Martian program will be successfully completed is presented by Sherry and Trauth in the following equation:

$$P-(1-P_L)^N_L\,(1-P_F)^N_F\,(1-P_o)^W_o\,(1-P_V)^N_L \qquad (1)$$

where

P the probability of successfully completing the Martian exploration program with the risk of contaminating Mars of $(1-P)$

Table 6. *Comparison of Planetary Quarantine Models (after Schalkowsky and Cooley, 1966, p. 10).*

Item	Description	Planetary Contamination Parameters			Biological Judgment Parameters		Allocation Parameters			Implementation Parameters		
		P_c	n_L	n_U	p_G	p'_G	$n_L P$	$n_U P^i$	p_R	p_N	p'_R	p'_T
1	Sagan and Coleman	10^{-3}	667(1)	30	10^{-2}	1	5×10^{-4}	5×10^{-4}	1	2×10^{-4}	1	4×10^{-5}
2	Corrected values of Sagan and Coleman(2)	10^{-3}	667(1)	30	10^{-2}	1	5×10^{-4}	5×10^{-4}	1	7.5×10^{-5}	1	2×10^{-5}
3	COSPAR	10^{-3}	667	17	10^{-2}	1	5×10^{-4}	5×10-4	1	10^{-4}	1	3×10^{-5}
4	Present model case (a)	10^{-3}	70	30	10^{-3}	1	5×10^{-4}	5×10^{-4}	1	7×10^{-3}	1	1.7×10^{-5}
5	Present model case (b)	10^{-3}	70	30	10^{-3}	1	7×10^{-5}	9.3×10^{-4}	1	10^{-3}	1	3.1×10^{-5}

(1) This value of n_L is not explicitly given in the Sagan-Coleman analysis. It has been calculated using data provided on the desired number of successful experiments and the various success probabilities, and by adding a probability of 0.9 that the capsules launched will successfully land on Mars.

(2) Differences between values in this item and item 1 stem largely from the erroneous use by Sagan and Coleman of logarithms to the base 10 rather than base e as called for in their formulation.

$(1-P_L)$ the probability that a lander capsule does not contaminate Mars

N_L the minimum number of lander missions needed to successfully complete the lander phase of experimentation

$(1-P_F)$ the probability that a flyby capsule does not contaminate Mars

N_F the minimum number of flyby missions needed to successfully complete the flyby phase of experimentation

$(1-P_O)$ the probability that an orbiter capsule does not contaminate Mars

N_O the minimum number of orbiter missions needed to successfully complete the orbiter phase of experimentation

$(1-P_V)$ the probability that a bus vehicle from a lander mission does not contaminate Mars

By taking the natural logarithms of both sides of equation (1), it becomes

$$\ln P = N_L \ln (1-P_L) + N_F \ln (1-P_F) + N_O \ln (1-P_O) + N_L \ln (1-P_V) \qquad (2)$$

The authors then break equation (2) into these components:

$$K_L \ln P = N_L \ln (1-P_L) \qquad (3L)$$

$$K_F \ln P = N_F \ln (1-P_F) \qquad (3F)$$

$$K_O \ln P = N_O \ln (1-P_O) \qquad (3O)$$

$$K_V \ln P = N_L \ln (1-P_V) \qquad (3V)$$

where

$$O \leq K_L, K_V, K_F, K_O \leq 1, \text{ and } K_L + K_F + K_O + K_V = 1 \qquad (4)$$

They then write equation (3) as

$$P^{K_L} = (1-P_L)^{N_L} \qquad (5L)$$

$$P^{K_F} = (1-P_F)^{N_F} \qquad (5F)$$

$$P^{K_O} = (1-P_F)^{N_O} \qquad (5O)$$

$$P^{K_V} = (1-P_V)^{N_L} \qquad (5V)$$

The equations above (5) represent the authors' attempt to assign the

requirements for a completely successful program to its constituent parts. As an example, they state that if the lander phase makes up 48 percent of the Mars contamination threat, the flyby phase 24 percent, the orbiter phase 16 percent, and the bus vehicles 12 percent, then the K's can be determined because of the linearity of equation (2) as follows: $K_L = .1$, $K_F = .2$, $K_O = .3$, and $K_V = .4$. These values are regarded as parameters, since the actual percentages are unknown.

When they consider only the lander phase of a successful program, they find that N_L is the minimum number of missions required to satisfy the inequality:

$$E_L \leq \sum_{i=1}^{N_L} Z_{L,i} X_{L,i} \tag{6}$$

where

- E_L the total number of experiments intended to be performed in the lander phase
- N_L the minimum number of successful lander missions needed to perform E_L experiments
- $Z_{L,i}$ the percentage of experiments on board the i^{th} lander that must work in order to have the mission considered successful
- $X_{L,i}$ the number of experiments on board the i^{th} lander mission

$Z_{L,i}X_{L,i}$ assumes only integer values. Thus, the number N_L depends on E_L, $Z_{L,i}$, $X_{L,i}$. In the actual calculations, N_L was treated simply as a parameter of the model and its relationship to E_L, $Z_{L,i}$, and $X_{L,i}$ was neglected.

Sherry and Trauth state (Sherry and Trauth, 1966, p. 12):

> The decision to simplify N_L in this manner was made for practical reasons. At this stage, E_L, $A_{L,i}$, and $X_{L,i}$ are themselves still parameters which will be influenced by time and technique. If, however, one treats the number of lander missions as a parameter, one can neglect the undetermined values of E_L, $Z_{L,i}$, and $X_{L,i}$, and still obtain valuable information. Thus, values have been chosen for N_L, and no concern has been given to its precise relation to E_L, $X_{L,i}$, and $Z_{L,i}$, other than that it does satisfy inequality (6). (The same approach holds for N_F, and N_O.)

The authors also take into account the probability of a mission failure by modifying equation (1) in terms of a truncated negative binomial distribution. They use the lander phase of the program as an example, given the following:

1. $(N_L - 1)$ lander missions have been successfully completed without contaminating Mars
2. J_L lander missions have failed without contaminating Mars
3. The $(N_L + J_L)^{th}$ lander mission will be successful and not contaminate Mars

Then, they designate

$(N_{L_{J_L}}-1+J_L)$	the number of ways J_L failures can occur in N_L-1+J_L lander missions
$P_{L,S}$	the probability of a successful lander mission
$(1-P_{L,S})$	the probability of an unsuccessful lander mission
$(1-P_L)$	the probability that a lander mission does not contaminate Mars
N_L	the total number of successful lander missions
M_L	the total number of unsuccessful lander missions

Therefore, P^{K_L} in equation $(5L)$ becomes the probability that N_L lander missions in N_L+M_L landed missions are successfully accomplished with no contamination of Mars. Equation $(5L)$ then becomes

$$P^{K_L}=\sum_{J_L=0}^{M_L}(1-P_L)^{N_L+J_L}(N_{L_{J_L}}+J_L-1)\,(P_{L,S})^{N_L}\,(1-P_{L,S})^{J_L} \qquad (7L)$$

Sherry and Trauth emphasize the point that P^{K_L} is a combined probability of both mission success and no contamination, based on a finite number of missions (N_L+M_L).

By defining $P_{F,S}$ as the probability of a successful flyby mission and $P_{O,S}$ as the probability of a successful orbiter mission, equations $(5F)$, $(5O)$, and $(5V)$ become

$$P^{K_F}=\sum_{J_F=0}^{M_F}(1-P_F)^{N_F+J_F}\,(N_{F_{J_F}}-1+J_F)\,(P_{F,S})^{N_F}(1-P_{F,S})^{J_F} \qquad (7F)$$

$$P^{K_O}=\sum_{J_O=0}^{M_O}(1-P_O)^{N_O+J_O}(N_{O_{J_O}}-1+J_O)\,(P_{O,S})^{N_O}(1-P_{O,S})^{J_O} \qquad (7O)$$

$$P^{K_V}=(1-P_V)^{N_L+M_L} \qquad (7V)$$

To get the needed generalization of equation (1) and the expression for a successful completion of the Martian program with lander, flyby, and orbiter missions without contaminating the planet, the authors multiply equations $(7L)$, $(7F)$, $(7O)$, and $(7V)$:

$$P=\sum_{J_L=0}^{M_L}(1-P_L)^{N_L+J_L}\binom{N_L-1+J_L}{J_L}(P_{L,S})^{N_L}(1-P_{L,S})^{J_L}\cdot$$

$$\cdot \sum_{J_F=O}^{M_F} (1-P_F)^{N_F+J_F} \binom{N_F-1+J_F}{J_F} (P_{F,S})^{N_F}(1-P_{F,S})^{J_F} \qquad (8)$$

$$\cdot \sum_{J_O=O}^{M_O} (1-P_O)^{N_O+J_O} \binom{N_O-1+J_O}{J_O} (P_{O,S})^{N_O}(1-P_{O,S})^{J_O}$$

$$\cdot (1-P_V)^{N_L+M_L}$$

Probabilities of Contaminating Mars Sherry and Trauth are particularly concerned with the probability that a given lander will contaminate Mars (P_L), which is seen as a function of the following:

1. $k \geq O$, the number of viable non-Martian micro-organisms present on the lander capsule
2. $P(k)$, the probability that there are exactly k viable non-Martian micro-organisms present on the lander capsule as it impacts Mars
3. The position of these micro-organisms (exterior or interior)
4. $P_R(\tau|k)$, the probability that exactly τ viable non-Martian micro-organisms, given exactly k on board, are released on the Martian surface
5. $P_B(\tau)$, the probability that, given the release of τ viable non-Martian micro-organisms on the Martian surface, future scientific exploration of the planet is biased

P_L is then expressed as

$$P_L = \sum_{k=1}^{\infty} \left\{ \sum_{\tau=1}^{k} P_R(\tau|k) P_B(\tau) \right\} P(k) \qquad (9)$$

$P(k)$ represents the probability that there are k viable terrestrial organisms on the lander capsule as it impacts the Martian surface. The value is a function of the final sterilization cycle and the chance of the capsule's becoming contaminated during the period between sterilization and impact. In previous models, $P(k)$ was only the probability that k organisms would survive the dry heat sterilization cycle. In the Sherry and Trauth case, it depends on the type of organism (α), initial population (n_o), exposure time (t), and sterilization temperature (T). Thus, the probability of a micro-organism's surviving would be $p\ (\alpha, t, T)$. They assume that the organisms die independently of one another, so that a binomial distribution can be used for $P(\chi)$, leading to

$$P(k) = \binom{n_o}{k} [p(\alpha, t, T)]^k [1 - p(\alpha, t, T)]^{n_o-k} \qquad (10)$$

that is, the probability that from a population of n_o type α organisms, k numbers will survive the sterilization cycle of t time and T temperature.

Sherry and Trauth propose that, given k organisms on the vehicle, the conditional probability that τ viable terrestrial micro-organisms will be released on the Martian surface is $P_R(\tau/k)$, which depends on whether the organisms are on the interior or exterior of the capsule. They go on to define the following:

$P_E(k_1\|k)$	the probability of k_1 viable non-Martian micro-organisms on the exterior of the lander capsule, given a total of k on the lander
$P_I(k_2\|k)$	the probability of k_2 viable non-Martian micro-organisms in the interior of the lander capsule, given a total of k on the lander
$\hat{P}_R(E\|\tau_1\|k_1)$	the probability of release of τ_1 viable non-Martian micro-organisms from the exterior, given that there are k_1 on the exterior of the lander capsule
$\hat{P}_R(I\|\tau_2\|k_2)$	the probability of release of τ_2 viable non-Martian micro-organisms from the interior, given that there are k_2 on the interior of the lander capsule
$P_R(E\|\tau_1\|k)$	the probability of release of τ_1 viable non-Martian micro-organisms from the exterior of the lander capsule, given a total of k on the lander
$P_R(I\|\tau_2\|k)$	the probability of release of τ_2 viable non-Martian micro-organisms from the interior of the lander capsule given a total of k on the lander
$P(\tau_1, \tau_2\|k)$	the probability of release of τ_1 exterior and τ_2 interior viable non-Martian micro-organisms given a total of k on the lander

They then represent $P_R(\tau/k)$ by

$$P_R(\tau|k) = \sum_{\tau_1+\tau_2=\tau} P_R(\tau_1, \tau_2|k) \tag{11}$$

where

$$P_R(\tau_1, \tau_2|k) = P_R(E|\tau_1|k) \cdot P_R(I|\tau_2|k) \tag{11a}$$

where

$$P_R(E|\tau_1|k) = \sum_{k_1=\tau_1}^{k} \hat{P}_R(E|\tau_1|k_1)P_E(k_1|k) \tag{11b}$$

and where

$$P_R(I|\tau_2|k) = \sum_{k_2=\tau_2}^{k} \hat{P}_R(I|\tau_2|k_2)P_I(k_2|k) \tag{11c}$$

The authors then analyze equation (9) in greater detail. First, they consider

$$P_L = \sum_{k=1}^{\infty} \left\{ \sum_{\tau=1}^{k} P_R(\tau|k) P_B(\tau) \right\} P(k) \tag{12}$$

and set

$$P_D(k) = \sum_{\tau=1}^{k} P_R(\tau|k) P_B(\tau) \tag{12a}$$

The value of $P_D\ (k)$, the probability of contaminating Mars when there are k organisms on a capsule, cannot be precisely determined, and is therefore considered a parameter of the model. $P_D\ (k)$ is assumed to be equal to P_D for all k. "This . . . does not distort reality too much, because $P_D\ (k)$ is a non-negative and bounded by 1 for all k" (Sherry and Trauth, 1966, p. 19). Equation (12) then becomes

$$P_L = P_D \sum_{k=1}^{\infty} P(k) \tag{12b}$$

Summing the above equation gives

$$P_L = P_D([1 - P(O)]) \tag{12c}$$

or

$$P_L = P_D \rho \tag{13L}$$

P_F and P_O can be treated similarly, and a comparable equation developed:

$$P_F = P_{I,F} \sum_{k=1}^{\infty} P_D(k) \hat{P}(k) \tag{13F}$$

and

$$P_O = P_{I,O} \sum_{k=0}^{\infty} P_D(k) \hat{P}(k) \tag{13O}$$

where

P_I the probability that a flyby (orbiter) capsule impacts the planet

$\hat{P}(k)$ $P(k)$ of equation (10), with $p(\alpha, t, T)$ based on (perhaps) different values of t, and/or T

Non-contamination Probability Regarding the lander phase, N_L, M_L, K_L, and $P_{L,S}$ are given as parameters with the inequality $P \geq \hat{P}$. In this case, $\hat{P}$ is 0.999, the least acceptable value for P and the non-contamination probability accepted by COSPAR.

Sherry and Trauth believe that the object, then, is to solve the following inequality for P_L:

$$\hat{P}^{K_L} \leq P^{K_L} = \sum_{J_L=0}^{M_L} (1 - P_L)^{N_L + J_L} \binom{N_L + J_L - 1}{J_L} (P_{L,S})^{N_L} (1 - P_{L,S})^{J_L}$$

This is done to obtain a number $\hat{P}_L$ such that for all $P_L \leq \hat{P}_L$ the inequality obtains. They state that if one solves

$$P^{KL} = \sum_{J_L=0}^{M_L} (1-P_L)^{N_L+J_L} \binom{N_L+J_L-1}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L}$$

the solution, if it exists, will be $\hat{P}_L$. The objective, then, is to solve the $(N_L+M_L)^{th}$-degree polynomial in P_L for $\hat{P}_L$. They further believe that because N_L+M_L is relatively large, the solution must be obtained numerically, and some attention must be paid to the accuracy of the solution.

Consequently, the calculations produce an upper bound P_L $(U.B.)$, and a lower bound, P_L $(L.B.)$, for the maximum acceptable value of P_L. The inequalities below (14) are solved numerically for P_L $(U.B.)$ and P_L $(L.B.)$, when $P=\hat{P}$:

$$P^{KL}-\epsilon \leq \sum_{J_L=0}^{M_L} [1-P_L(U.B.)]^{N_L+J_L} \binom{N_L-1+J_L}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \tag{14a}$$

$$\leq P^{KL} \tag{14b}$$

$$= \sum_{J_L=0}^{M_L} (1-P_L)^{N_L+J_L} \binom{N_L-1+J_L}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \tag{14c}$$

$$\leq \sum_{J_L=0}^{M_L} [1-P_L(L.B.)]^{N_L+J_L} \binom{N_L-1+J_L}{J_L} (P_{L,S})^{N_L} (1-P_{L,S})^{J_L} \tag{14d}$$

$$\leq P^{KL}+\epsilon \tag{14e}$$

This then produces

$$P_L(L.B.) \leq P_L \leq P_L(U.B.) \tag{15}$$

or

$$P_L(L.B.) \leq \rho P_D \leq P_L(U.B.) \tag{16}$$

or

$$\frac{P_L(L.B.)}{P_D} \leq \rho \leq \frac{P(U.B.)}{P_D} \tag{17}$$

Sherry and Trauth maintain that these calculations have demonstrated that this approach provides an excellent bound on the maximum acceptable value of p for small ϵ. Similar maximum values can be obtained for P_F and P_O, particularly

$$P_F(L.B.) \leq P_F \leq P_F(U.B.) \tag{18}$$

and

$$P_O(L.B.) \leq P_O \leq P_O(U.B.) \tag{19}$$

But the maximum value they give for P_V is

$$P_V = 1 - P\,\frac{K_V}{D} \tag{20}$$

where

$$D = N_L + M_L \text{ and } P = \hat{P}$$

The authors also point out some of the conceptual difficulties in the contamination models developed by Sagan and Coleman, Schalkowsky, and Cornell. The latter two based their models on the Sagan-Coleman approximation below:

$$\ln p^{-1} \simeq \frac{\sigma P_m N}{P_e P_+ \chi} + nP_i \tag{21}$$

Sherry and Trauth suggest that there is considerable confusion regarding the definition of σ in the approximation. Sagan and Coleman refer to it as "the mean number of organisms deposited" and as "the probability that a single viable micro-organism be deposited" on the surface of Mars. In contrast, Cornell defines σ as "the mean number of organisms per capsule," but also says that σ may be defined as "the probability that a spacecraft landing on Mars will be contaminated" by using the relation $P_- = \sigma P_m$. When σ is treated as such a probability, however, $P_L = \sigma P_m$ is an incorrect mathematical relation, since P_L is a plural concept, while P_m, the "probability that a given micro-organism landed on the surface of Mars will be able to multiply and contaminate a sizable fraction of the planet," is a singular concept (Sherry and Trauth, 1966, p. 25).

In his summary of the Sagan and Coleman model, Schalkowsky also confuses mean number and probability, according to Sherry and Trauth. He defines σ as the "probability of one viable micro-organism on the surface of Mars due to a single lander," and then as

$$\sigma = P_N \cdot P_R \tag{22a}$$

where

P_N the probability of one viable micro-organism aboard the lander

P_R the mean probability that one micro-organism, if present, will be released from the lander and deposited on the Martian surface

Thus, P_N, a sterilization criterion, is used as a "probability of one viable

micro-organism aboard the lander" (Sherry and Trauth, 1966). But Schalkowsky's equation states that

$$P_N = N_o \cdot 10^{-t/D} \tag{22b}$$

with

- N_o as the initial population of micro-organisms on the lander (prior to the application of dry heat)
- t as the length of time dry heat is applied at a particular fixed temperature
- D as the time it takes to reduce a single-species population by a factor of 10 at a fixed temperature

Sherry and Trauth suggest that although the P_N used above in equation (22a) is referred to as a "probability," it is an expected number, i.e., σ and P_N are expected numbers of organisms rather than "the probability of a single viable micro-organism aboard a lander." However, they admit that Schalkowsky later considered this problem and showed that, when $P_N \ll 1$, P_N is a good numerical approximation of the probability of a single organism's being aboard a lander. Consequently, Sherry and Trauth replace

$$P_- \simeq \sigma P_m \tag{23a}$$

with

$$P_L = \rho P_D \tag{23b}$$

because it eliminates the confusion about the definition of σ; p provides more information than σ, since the former is a probability and the latter an expected number; and the derivation of P_D is more realistic.

The authors caution against confusing $P_{L/S}$, the probability that a lander mission is successful, with P_+. The latter term was originally used by Sagan and Coleman as the mean probability that a lander on the Martian surface will succeed in its biological experiment. Subsequently, P_+ referred to the probability of a successful landing, with no reference to experimental success.

The last major conceptual problem the authors find in the Sagan-Coleman model, later seen in the work of Schalkowsky and Cornell, is that they consider j ($J_L = j$) to run from 0 to ∞:

$$p = \sum_{j=0}^{\infty} \binom{N+j-1}{j} P_+^N (1-P_+)^J (1-P_-)^{N+j} \tag{24}$$

or

$$P=\sum_{J_L=o}^{\infty}\binom{N_L+J_L-1}{J_L}P_{L,S}^{N_L}(1-P_{L,S})^{J_L}(1-P_L)^{N_L+J_L} \quad (25)$$

P (in closed form) is solved by summing J_L from 0 to ∞:

$$P=\left[\frac{P_{L,S}(1-P_L)}{1-(1-P_{L,S})(1-P_L)}\right]^{N_L} \quad (26)$$

But they view this as a (Sherry and Trauth, 1966, p. 29)

. . . distortion from the reality of the Martian Exploration Program, since equations (25) and (26) demand that we continue to send unmanned lander capsules to Mars until we have N_L successful missions (apparently without regard for the limitations of time or finances).

Martian Exploration Program Sherry and Trauth contend that sending an unlimited number of missions to Mars is unrealistic and not the intention of the space program. Instead, the Martian Exploration Program should be formulated in terms of the finite aims and constraints that follow:

1. To successfully complete N ($N=N_L+N_F+N_O$) missions
2. To keep the risk of contamination of Mars small
3. To accomplish (1) and (2) by attempting no more than N' ($N'=N_L+M_L+N_F\,3M_F+N_O+M_O$) space missions

They go on to state the following (Sherry and Trauth, 1966, p. 29):

When N_L, M_L, P, K_L, and $P_{L,S}$ (in the case of the lander phase of the program) are specified, one attempts to solve equation (7L) for P_L. Since M_L is a fixed finite number, two very interesting difficulties come to light. The first difficulty is that for certain values of the parameters (for example, $N_L=40$, $M_L=10$, $P=0.999$, $K_L=0.5$, $P_{L,S}=0.85$) no acceptable (between 0 and 1) value of P_L can be found that satisfies equation (7L).

However, this does not occur if the Sagan and Coleman equation is used in the closed form. That is, when equation (26) is solved, the result is

$$P_L=\frac{P_{L,S}[1-P^{(1/N_L)}]}{P_{L,S}[1-P^{(1/N_L)}]+P^{(1/N_L)}}$$

Here, $0\leq P_{L,S}\leq 1$, and P_L falls between zero and one, regardless of the value of $P_{L,S}$.

The second difficulty concerns the sensitivity of $P_{L,S}$ in equation (14). As an example, if $N_L=80$, $M_L=20$, $P=0.999$, and $K_L=1$, $P_{L,S}$ can be varied so as to make P_L as small as desired (see Table 7 below):

Table 7 *Making* P_L *as Small as Desired (after Sherry and Trauth, 1966, p. 30).*

$P_{L,S}$	P_L
0.95	1.18×10^{-5}
0.90	2.17×10^{-6}
0.89832	6.39×10^{-9}
0.8983185	7.49×10^{-12}

In this table, the relationship between P_L and $P_{L,S}$ is very sensitive in the area of $P_{L,S}=0.90$. When $P_{L,S}$ changes only slightly, this is reflected by a very great change in P_L, in the same direction, with a comparable change in $\rho(P_L=\rho P_D)$. Thus, severe sterilization methods would be required, and there would be difficult engineering problems. The authors emphasize that this sensitivity cannot be seen if the closed form of equation (26) is used.

CONTAMINATION FROM EJECTA AND EMISSIONS

Planetary contamination with terrestrial micro-organisms can occur as a result of ejecta and emissions from vehicles during flyby or orbit, as well as from the spacecraft's impacting the planet's surface.

Czarnecki et al. (1966) show the potential contaminating events of a flyby or orbiter in Figure 2. The authors developed the following equation to describe the probability of contamination from ejecta or emissions:

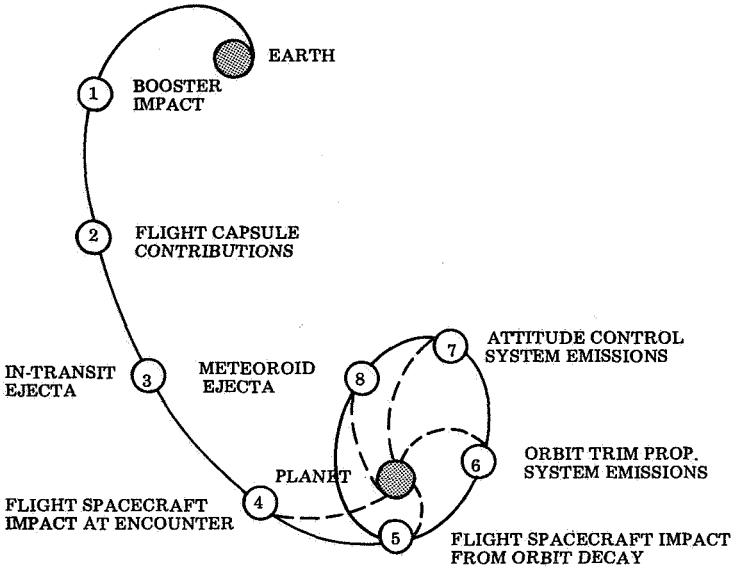
$$P_c = P_o \left[1 - \exp \left(- \sum_{j=1}^{n} r_j P_{1j} P_s \right) \right] \quad (1)$$

where

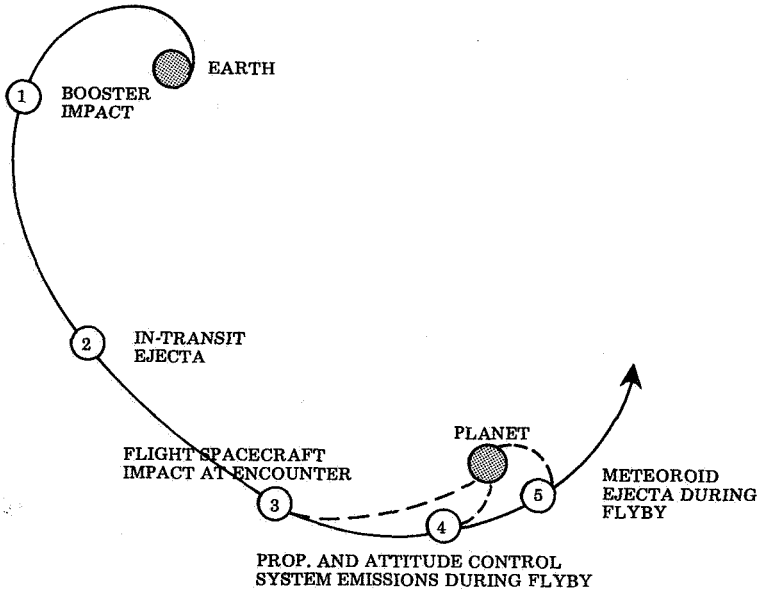
- P_c the probability of planetary contamination
- P_o the probability of all operational events occurring successfully up to the propulsion, reaction control system, or meteoroid impact events under consideration
- r_j the number of expected viable micro-organisms on or in the subsystem under consideration which are subject to possible release at the time of a propulsion, reaction control, or meteoroid impact event
- P_{1j} the probability of live escape of the micro-organisms as a result of a propulsion, reaction control system, or meteoroid impact event
- P_s the conditional probability of spore survival following ejection from the spacecraft, including survival from radiation exposure and planetary entry conditions and survival and propagation under the planet's surface environmental conditions

The specific sources of potential contamination are shown in the equation by the j subscripts in the r and P_1 terms.

An analysis of the terms in equation (1) suggests two critical questions. First, will terrestrial organisms survive planetary atmospheric entry?



PLANET ORBITING MISSION



PLANET FLYBY MISSION

Figure 2 *Potential Sources of Contamination for Orbiters and Flybys (after Czarnecki et al., 1966, p. 531).*

Second, if they do survive, will they grow and propagate in this environment? These matters are regarded as critical problems because of the sensitivity of the value of P_c in the equation to the values of P_s. When P_c is small, equation (1) is approximated by

$$P_c = P_o \sum_{\alpha=1}^{\eta} r_j P_{1j} P_s \tag{2}$$

However, since $P_s = P_{SA} P_{SUV} P_G$,

$$P_c = P_o \sum_{\alpha=1}^{\eta} r_j P_{1j} P_{SA} P_{SUV} P_G \tag{3}$$

The authors feel that if the P_s terms are small enough, the P_c apportioned to the contaminating events might be achieved without "establishing any design requirements relative to sterilization or decontamination of the spacecraft" (Czarnecki et al., 1966, p. 529).

Korenstein (1966) also studied the possible effects of contaminated particles being ejected from a Voyager spacecraft on the way to, or in, orbit around Mars. He discusses the distance by which the particles miss Mars as a function of their size, point of ejection, ejection velocity and direction, transfer trajectory, and aim point bias. For the orbiting phase, he computed the orbit lifetimes and defined the conditions under which the particles enter the lower Martian atmosphere. Korenstein concludes that the orbiting phase of the mission poses a significantly greater threat to the quarantine constraint than does the transit phase.

VENUS CONTAMINATION PROBABILITIES

There was some concern that Venus might have been contaminated by the flight of the U.S.S.R. *Venus 3* in 1965. Consequently, Schalkowsky (1966c) attempted to determine the planetary contamination probabilities of *Venus 3* and the effect of this flight on future quarantine requirements for the planet. He believes that there is a consensus that the polar caps and some parts of the atmosphere are the only areas in which terrestrial organisms might survive (e.g., Sagan, 1968).

Schalkowsky does not think that there was much chance that *Venus 3* contaminated the planet, thus making future quarantine restrictions unnecessary. However, he raises the question of the effect of the flight of *Venus 3* on the probability of planetary contamination occurring during the time period considered ($P_C \leq 10^{-3}$), and whether such a value is meaningful for determining standards for future Venus flights. On the basis of his own estimates, he concludes that an increase in P_C above 10^{-3} to 5×10^{-3} or even 10^{-2} is justified. At any rate, restrictions

on missions to Venus probably will not be as severe as those for Mars.

Brown (1966a) maintains that the surface temperature of Venus is probably high enough to prevent contamination with terrestrial microorganisms, making sterilization requirements unnecessary. However, there is some doubt about the high temperature estimate. If, on the basis of future evidence, the estimate should be lowered, Brown feels that Venus would become an exobiologically significant target. If this should be so, then Venus would require more stringent sterility criteria. However, as long as there is some doubt about its surface temperature, Brown suggests that no lander should be sent to Venus without undergoing sterilization procedures, and that any flyby should have at least the same trajectory control as those used with Martian flybys.

In a *Preliminary Report to COSPAR on the Prelaunch Probability of Contaminating Venus by the Mariner 1967 Mission* (undated and unsigned), it was stated that NASA policy established 3×10^{-5} as the maximum probability of accidentally contaminating Venus by the Mariner Venus 1967 mission. Haynes (1967) distinguishes two ways in which Venus could be contaminated by this mission: (1) the accidental impact of the spacecraft or of the Agena stage of the boost vehicle or (2) the release of viable organisms from the spacecraft, which would be deposited on the planet without the impact of the vehicle. Haynes points out that, since neither the Agena nor the spacecraft will be sterilized, their injection trajectories will have to be biased away from Venus; the Agena will carry a retrorocket to further deflect its trajectory. In the second case, with current spacecraft design, "the probability of ejecta . . . reaching the planet and subsequently growing and spreading is estimated to be less than 1×10^{-8}, hence negligible relative to satisfying the 3×10^{-5} constraint" (Haynes, 1967, p. 1).

Haynes reviewed NASA policy regarding the planetary quarantine requirements established for the Mariner Venus 67 Project and developed a prelaunch mathematical model for predicting the probability of contaminating Venus with terrestrial organisms. The NASA requirement is expressed as

$$P' = \sum_i (P'_I P'_R P'_G)\, i \tag{1}$$

where

- P'_I the probability of impact
- P'_R the probability that a viable organism from the spacecraft will be released onto the planet's surface or into its atmosphere
- P'_G the probability that a viable organism, present on the planet's surface or in the atmosphere and not previously heat sterilized, will grow and spread, contaminating the planet or its atmosphere

The summation is taken over the "i," i.e., the possible sources of contamination.

It is further stated that if the value of P'_R is taken to be less than unity and if there is an impact of the vehicle on the planet, some justification must be given. Haynes believes it is possible to justify such a reduction in the probability that the impact of a vehicle will release viable micro-organisms; he does not think that the change would be significant and assumes that $P'_R = 1.0$, which is a conservative estimate.

The value for P'_G is set at not less than 0.10, based on the hostile surface environment of Venus. The Planetary Atmospheres Subcommittee of the NASA Office of Space Sciences and Applications reported less than one chance in 10 that a random point of impact on the surface of Venus would have a temperature below 400 Kelvin; it was assumed that the probablity of the growth of terrestrial organisms would be at most 0.10. The SSB agreed with this analysis and, thus, equation (1) could be written as

$$P' = \sum_i P'_I P'_R \ (0.10)_i \tag{2}$$

In view of the two possible sources of contamination described above, equation (2) can be written as follows:

$$P' = P'_{I_A} P'_{R_A} (0.10) + P'_{I_S} P'_{R_S} (0.10) + \sum_i [P'_{I_E} P'_{R_E} (0.10)_i] \tag{3}$$

where

Subscript A the Agena impact
Subscript S the spacecraft impact
Subscript E the ejecta (the third item indicates the summation over the potential sources of ejecta contamination)

P'_{R_A} and P'_{R_S}, which are assumed to be 1.0, are then substituted into equation (3):

$$P' = P'_{I_A} \ (0.10) + P'_{I_S} \ (0.10) + \sum_i [P'_{I_E} P'_{R_E} \ (0.10)]_i \tag{4}$$

Haynes uses this form of the equation in his analysis. He examines each of the sources of ejecta (midcourse motor exhaust products, micrometeorite ejecta, and altitude control gas jets) in terms of their contribution to the probability of contaminating Venus.

The probability of contaminating Venus with terrestrial organisms carried by midcourse motor exhaust products is summarized by Haynes as follows:

$$P_{C_{MC}} = P_E P_I P_{UV} P_{SE} P_{gs}$$

where

P_E the probability of ejecting a viable organism
P_I the probability of achieving an impact trajectory
P_{UV} the probability of surviving the UV environment
P_{SE} the probability of surviving the entry heating load
P_{gs} the probability of growing and spreading on the surface of or in the atmosphere of Venus

By substituting estimated probabilities for each of these terms into the equation, the following result is obtained:

$$P_C = (0.1)\,(0.00001)\,(0.1)\,(0.1)\,(0.1)$$

Thus, $P_C = 10^{-9}$ is the estimated probability of contaminating Venus with organisms from midcourse motor ejecta.

Micrometeorite Possibilities A second potential source of contaminants is the possibility that micrometeorites would strike the spacecraft, dislodging micro-organisms which would then contaminate Venus. Haynes maintains that there is a less than 10^{-3} probability that the organisms, which would be dislodged in random directions, would be within the required 1° cone. Furthermore, there is less than a 0.01 probability of the ejecta's being within a band of a few meters per second so that the chance of an impact trajectory is considered to be 10^{-5} or less. The probability that the organisms will survive ultraviolet radiation and entry heating is 0.10; the probability of growth and spreading is estimated at 0.1. Thus, Haynes concludes

$$P_C = P_E P_I P_{UV} P_{SE} P_{gs}$$

$$P_C = (1.0)\ (0.00001)\ (0.1)\ (0.1)\ (0.1) = 10^{-8}$$

where 1.0 is the assumed probability of ejecting viable micro-organisms by this means.

The same approach is used by Haynes to determine the probability of contaminants coming from the altitude control gas jets. The probability of organisms escaping the altitude control system when an impact trajectory is achieved is

$$n = 5 \times 10^{-6} N$$

when

n the number of viable organisms that achieve an impact trajectory

N the total number of viable organisms in the spacecraft control system

Since all altitude control nitrogen must pass through two filters, and assuming that there are only about four viable organisms in the spacecraft tanks (Haynes, 1967, p. 8),

> . . . the probability of ejecting a single viable micro-organism times the probability of failure of the filters is 4×10^{-4}. Substituting this value for N in the preceding equation yields a probability of roughly 10^{-10} of contaminating Venus with gas from the altitude control system.

With these analyses in mind, Haynes believes there is less than a 10^{-8} probability of contaminating Venus with ejecta. That is considerably less than the quarantine constraint of 3×10^{-5} and the probability of contamination from the impact of a vehicle.

Haynes describes four ways in which there can be an accidental impact trajectory:

1. The spacecraft is injected into an impact trajectory that cannot be corrected with a maneuver because of a spacecraft malfunction.
2. Following the first maneuver, the spacecraft is on an impact trajectory that cannot be corrected with a second maneuver because of a malfunction in the spacecraft.
3. The spacecraft performs a first maneuver that misses the planet but also misses the desired target zone. A second maneuver is performed, resulting in a planet impact trajectory.
4. The spacecraft is on an impact trajectory following the first maneuver, and a second maneuver that also results in a planet impact trajectory is performed.

The probability of impact by the spacecraft is also described by the following equation:

$$P'_{I_S} = [P_{I/i}q_1 + P_1P_{I/1}(q_2 + P_2P_{I/2}) + P_1(1 - P_{I/1})P_{2/1}P_2P_{I/2}]P_i \quad (5)$$

where

$P'_{I/S}$ the probability of spacecraft impact at Venus
$P_{I/i}$ the probability of achieving an impact trajectory at injection
P_1 the probability of the spacecraft's being able to perform a first maneuver
q_1 $1 - P_1$ = the probability of the spacecraft's not being able to perform a first maneuver
P_2 the probability of the spacecraft's being able to perform a second maneuver, given a successful first maneuver
q_2 $1 - P_2$ = the probability of the spacecraft's being unable to perform a second maneuver, given a successful first maneuver
$P_{I/1}$ the probability of impact following the first maneuver

$P_{I/2}$ the probability of impact following the second maneuver
$P_{2/1}$ the probability of requiring a second maneuver even though the first maneuver did not result in an impact trajectory
P_i the probability of the spacecraft's being injected on a Venus trajectory during the 1967 opportunity

Impact by Launch Vehicle Haynes then determines the probability of the spacecraft's impacting Venus by making the following assumptions and using equation (6):

1. P_1, the probability of the spacecraft's being able to perform an initial maneuver is taken to be 0.98.
2. P_2, the probability of the spacecraft's being able to perform a second maneuver, given a successful first maneuver performance is taken to be 0.98. This reduction from 1.0 is basically the estimate of the small probability that the spacecraft would fail after the first maneuver but before a second maneuver, and also that a second maneuver uses a different set of valves in the propulsion system than was used in the successful first maneuver.
3. $P_{I/i}$, the probability of achieving an impact trajectory at injection is left as a variable, since it can be adjusted downward by biasing the launch trajectories away from the planet and vice versa. This number is computed by mapping the injection dispersions given by the covariance matrix of injection errors to the aiming point at the planet and integrating over the capture radius of the planet. For unbiased trajectories, this number varies from about 0.08 on the June 12 launch date to about 0.02 on the June 27 launch date.
4. $P_{I/1}$, the probability of achieving an impact trajectory following the first maneuver is computed by mapping the dispersions from the execution of the midcourse maneuver to the planet and integrating over the capture radius. This quantity is a function of the errors in the maneuver and the location of the target aiming point. For the Mariner Venus 67 mission, the aiming point will be selected in an a priori probability of impact following the first maneuver of 3×10^{-4} or less.
5. $P_{2/1}$, the probability of performing a second maneuver even if the first maneuver does not result in an impacting trajectory, is computed by finding statistically the size of the execution errors resulting from the first maneuver, mapping these to the planet, and integrating over the region of acceptable encounter. For Mariner Venus 67 this number is assumed to be 0.50.
6. $P_{I/2}$, the probability of impact following the second maneuver, is determined by finding the statistical size of the execution errors resulting from the second maneuver, including orbit determination

uncertainties, mapping these to encounter, and integrating over the planet capture area. Since a second maneuver is normally correcting errors from the first maneuver, it is expected to be very small and, hence, the errors associated with it should be small. For the Mariner Venus 67 mission, the second maneuver target aiming point will be selected so that an a priori probability of achieving an impact trajectory will be less than 10^{-6}.

Haynes derives a similar equation for the probability of impact by the launch vehicle:

Thus,

$$P'_{I_A}=P_i[P_{I/i}q_r+(1-P_{I/i})P_rP_{I/r}] \tag{6}$$

where

q_r the probability of the Agena retrorocket's not firing
P_r $1-q_r$
$P_{I/r}$ the probability of achieving an impact trajectory after retrofire given that trajectory was nonimpacting prior to retrofire (Haynes assumes that if the Agena attains an impact trajectory and the retrorocket fires, there would be a zero probability of an impact trajectory)

In order to calculate the probability of the Agena's attaining an impact trajectory, Haynes makes two assumptions:

1. P_r, the probability of a successful retromaneuver, given successful injection, is 0.99.
2. $P_{I/r}$, the probability of impact following a retromaneuver, is calculated by integrating the mapped injection errors over the capture area of the planet from an aim point biased away from the planet by the amount the retromaneuver moves the Agena trajectory. For the Mariner Venus 67 trajectories, this number is always less than 10^{-6}.

He then substitutes these figures into equation (6), pointing out that the second term in the equation is at least two orders of magnitude smaller than the first and of the order 10^{-6}. Therefore,

$$P'_{I_A}\approx P_iP_{I/i}q_r \tag{7}$$

By substituting analogous numbers into equation (5), it becomes evident that the last two terms are of the order 10^{-6}, and Haynes thinks that they can be neglected. Thus,

$$P'_{I/S}=P_iP_{I/i}q_1 \tag{8}$$

He then substitutes equations (7) and (8) into equation (4) and, keeping in mind that the third term of equation (4) due to ejecta is negligible compared to the 3×10^{-5} constraint, he arrives at

$$P' = P_i P_{I/i} (q_r + q_1) \ (0.10) \tag{9}$$

Since $P' \leq 3 \times 10^{-5}$, he rearranges equation (9) using $q_r = 10^{-2}$ and $q_1 = 2 \times 10^{-2}$. This results in

$$P_{I/i} \leq \frac{0.01}{P_i} \tag{10}$$

However, Haynes cautions that $P_{I/i}$ for unbiased trajectories is between 0.08 and 0.02 depending on the launch date. In order to reduce $P_{I/i}$ to an acceptable level, the trajectories must be biased away from Venus (Haynes, 1967, p. 15).

The Mariner Venus 67 trajectories have been biased so that on each day of the launch period the probability of obtaining an impact trajectory at injection is less than 0.01.

Haynes' analysis, therefore, shows that the probability of the Mariner Venus 67 mission's contaminating the planet Venus is less than 3×10^{-5}.

Craven et al. (1968) reported on *A Preliminary Quarantine Analysis of a Possible Mariner Venus 1972 Mission,* in which planetary quarantine requirements were derived from previous constraints established for other missions. The Mariner Venus 67 mission, similar to the 1964 Mariner Mars mission, was constrained to a contamination probability no greater than 3×10^{-5}. In contrast, the Voyager Mars 1973 mission (postponed until 1975), which was to be a more complex operation because two capsules (for landing) and two spacecraft (for long-term orbit) were to be launched on a single vehicle, was to have the following constraints:

1. Probability of contamination due to each sterilized capsule, no greater than 1×10^{-6} (for two capsules: 2×10^{-6})
2. Probability of contamination due to each spacecraft and its ejecta, no greater than 3×10^{-5} (for two spacecraft: 6×10^{-5})
3. For unsterilized items common to both spacecraft, such as launch vehicle stages and adapters, probability of contamination to be included in the probability allocation for the two spacecraft

Summing these values gives a total allowable contamination probability for the mission of 6.2×10^{-6}.

Individual Missions The probability of contamination for individual missions, P_{cm}, requires an upper bound for the number of missions flown, n_M. Craven et al. consider 30 missions to be a reasonable estimate, so

that the following equation represents the policy directive applied to one mission:

$$10^{-3} \geq 1-(1-P_{CM})^{n_M} \geq n_M P_{CM}\left[1-\frac{(n_M-1)}{2}P_{CM}\right] \tag{1}$$

The authors continue (Craven et al., 1968, p. 5):

> Substituting the value 30 for n_M, one finds that if the probability of contamination per mission, P_{CM}, is kept less than or equal to 3.3×10^{-5}, the NASA Policy Directive is satisfied. Thus, in the following analysis for a *Mariner* Venus 1972 mission, the probability of contamination for the mission, P_{CM72}, will be taken as less than or equal to 3.3×10^{-5}. The value for P_{CM} agrees with the value used for the *Mariner* series. It appears, however, to conflict with $P_{CM}\leq 6.2\times10^{-5}$ for the *Voyager* Mars 1973 mission, but it agrees if it is taken into account that the *Voyager* Mars 1973 mission is, in reality, two missions using one launch vehicle.

Craven et al. (1968) adapted a quarantine equation from Light et al. (1967) that was used for the Mariner Venus 67 analysis:

$$P_{CM72}=P_{(PV)}+P_{(LV)} \tag{2}$$

where

- $P_{(PV)}$ the probability of planetary contamination due to the planetary vehicle (PV)
- $P_{(LV)}$ the probability of planetary contamination due to the launch vehicle (LV)

They then expanded the contamination probability resulting from the planetary vehicle, isolated from equation (1), as follows:

$$P_{(PV)}=P+P' = n_L(P_I P_S P_R P_G)+\sum_i (P_I' P_S' P_R' P_G)_i \tag{3}$$

where

- P the probability of contamination due to the lander(s)
- P' the probability of contamination due to sources other than the lander(s) (the form of this expression depends on the particular mission profile)
- n_L the number of landers per mission
- P_I the probability of a lander's impacting the planet
- P_S the probability of at least one viable micro-organism on a lander as it impacts the planet

P_R the probability of an organism on a lander which has undergone a terminal sterilization cycle (TSC) being released onto the planetary surface

P_G the probability of a released organism's growing on the planetary surface and biasing future experiments

$\sum_i$ the summation taken over the i sources of possible nonlander contamination, such as the booster, spacecraft, biobarrier, spacecraft ejecta, etc.

P'_I the probability of impact of one of these sources

P'_S the probability of at least one viable micro-organism on one of these sources upon impact

P'_R the probability of a viable organism from the impacting item being released onto the surface of the planet or into its atmosphere

The authors note that before equation (3) can be used, the growth and release factors must be defined. The probability of growth was estimated to be 1×10^{-4}, lower than that for other missions. In regard to the probability of release of a viable micro-organism from a capsule, they set this as near unity. The probability that a viable micro-organism will be released from an unsterilized spacecraft, launch vehicle, or debris is thought to be similar to the probability that the object will be contaminated at impact. The probability of release is said to be near unity except for the spacecraft and biobarrier, which are subject to high entry temperatures.

Craven et al. suballocate the allowable contamination probability (33×10^{-6}) for the 1972 Venus mission by assigning 2×10^{-6} to the launch vehicle and 31×10^{-6} to the planetary vehicle. They believe that the relatively low value used for the launch vehicle (Craven et al., 1968, pp. 6–7)

> . . . can be met by following a predetermined guidance policy that provides for aimpoint biasing. Previous operational experiences with Mariner Mars 1964 and Mariner Venus 67 have proved the adequacy of the biasing technique. The relatively higher value allocated to the planetary vehicle has been chosen to allow for possible accidental impact of the intact planetary vehicle in case of no separation and for possible accidental impact of the spacecraft, capsule, bio-barrier, and debris in case of separation.

TREATY AND MEETINGS ON SPACECRAFT STERILIZATION

A multilateral "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies" was signed on January 27, 1967, in Washington, D.C., London, and Moscow, in behalf of the U.S., the United Kingdom, the U.S.S.R., and a number of other countries. Article IX of the treaty states, in part: "States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination" ("Treaty," 1967, p. 2416). The treaty provides that any of its parties can request consultation with any other party concerning the latter's activities or experiments which might be harmful to the use of outer space.

The COSPAR Consultative Group on Potentially Harmful Effects of Space Experiments met in London on July 22, 1967. A report by Hedén and Imshenetsky on the meeting of the Panel on Standards for Space Probe Sterilization and the Symposium on Sterilization Techniques for Instruments and Materials as Applied to Space Research (London, July 18–22, 1967) was received. Six working parties were formed at the COSPAR Symposium to consider the areas of (1) a contamination log, (2) the probability of release and growth of micro-organisms, (3) the probability of contamination of Mars by unsterilized flyby or orbiting spacecraft, (4) gaseous sterilization, (5) special problems and difficulties in spacecraft sterilization, and (6) monitoring techniques.

The working party concerned with the contamination log affirmed its support for (1) the 1966 COSPAR (Vienna) resolution that suggested a basic or maximum probability of 1×10^{-3} that a planet will be contaminated during the period of biological exploration and (2) the application of this criterion to the Mars missions and the exploration of the other planets. It particularly emphasized the recommendation that, within 3 months after launch, the computations and sterilization procedures used by members to prevent contamination should be made available to COSPAR. A guideline for the preparation of such reports was described. The working party also agreed at that time that it was generally held that the probability that random types of viable micro-organisms deposited on

random areas of Mars would grow and spread was less than 1.0, but greater than 10^{-3}. In view of the uncertainty of these estimates, they suggested that this recommendation be replaced by a more general suggestion that the value assigned to this probability be carefully and conservatively established, taking into account all pertinent information.

The report of the working party on the probability of release and growth concluded that the probability of growth of viable terrestrial microorganisms and the release of single organisms from the interiors of solids, which have been considered in terms of the worst case (unity), should be revised. The growth probability is between 1×10^{-2} and 1×10^{-8}, and, taking a conservative approach, member nations were advised to use values for P_G of not less than 1×10^{-3}. The working party also urged members to conduct experiments to better define the release probability, in order to justify a value of unity or less.

The Mathematical Models Subcommittee of the American Institute of Biological Sciences Spacecraft Sterilization Advisory Committee met at Florida State University, February 8–9, 1967. An effort was made to arrive at some agreement on the planetary quarantine program in terms of international commitments, and various aspects of specific quarantine models were discussed.

Separate groups within the subcommittee drafted summary statements expressing their position on various aspects of planetary quarantine policy and efforts. For example, Wolfson, Dillon, and Craven wrote, "It has been and will continue to be a policy of the United States Government, that will be implemented by NASA, to maintain the possibility of accidentally contaminating Mars at a very low level" (Mathematical Models Subcommittee, 1967, p. 10). However, they felt that no international organization would be able to clearly define a contamination constraint, specify the parameters, or reach some agreement on this definition within the decade of primary interest. They attributed this situation to the lack of data for establishing mathematical probability expressions, suggesting that NASA set the guidelines and criteria for each U.S. project and continue to make public the steps taken to implement this policy.

INTERNATIONAL PLANETARY QUARANTINE STANDARDS

A statement on the formulation of international planetary quarantine standards was presented by Schalkowsky, who recommended that international standards be established in terms of "(a) the probability $P(n)$ that a single landing vehicle will contaminate the planet and (b) the probability $P(n')$ that a single non-landing vehicle will lead to the contamination of the planet" (Mathematical Models Subcommittee, 1967, p. 11). He includes the following parameters in the basic framework for these standards:

n	the number of landers during the period of unmanned exploration
n'	the number of non-landers during the period of unmanned exploration, $P(n_i)$, which is the same as $P(n)$ in (a) above, except that the i indicates it may vary from mission to mission, $P(n'_j)$, which is similarly related to $P(n')$
$P \doteq \sum_{i=1}^{n} P(n_i) + \sum_{j=1}^{n'} P(n'_j)$	the probability of contaminating a planet during the entire period of biological exploration

Schalkowsky points out that simplifying assumptions can be made to reflect the uncertainties in the parameters of the equation for P, until a broader base for their selection can be attained. These assumptions are

1. All the $P(n_i)$ are the same for the n flights to be considered, i.e., $P(n_i) = P(n)$
2. All the $P(n'_j)$ are the same for the n' flights to be considered, i.e., $P(n'_j) = P(n')$

In view of the fact that $P(n)$ and $P(n')$ will be considerably less than unity,

$$P = nP(n) + n'P(n') \tag{1}$$

Schalkowsky suggests that the quarantine criteria obtainable from equation (1) should be stated in the following form:

$$P(n) < \frac{P}{n} \tag{2}$$

$$P(n') < \frac{P}{n'} \tag{3}$$

Berger, Brown, and Trauth provide an illustrative model for $P(n)$ as defined by Schalkowsky:

$$P(n) = P(N \geq 1) = \sum_{N=1}^{\infty} p(N)$$

Where N = number of viable organisms reaching the planet and biasing experiments,

$p(N) = \Sigma P_i(r_i) p_i(z|r) p(N_i|z) =$ the density function of viable organisms reaching the planet

where

z	the number of viable organisms reaching the planet
r_i	the event of release from the i^{th} source
$P_i(r)$	the probability of being released by source i
$p_i(z\|r)$	the density of viable organisms reaching the planet given release from source i
$p(N_i\|z)$	the conditional density of N_i viable organisms biasing the experiment, given z of them reached the planet

$$= \binom{z}{N_i} P(b)^{N_i}[1-P(b)]^{z-N_i}$$

where $P(b)$ is the probability of one viable organism's biasing an experiment

Cornell summarized the statements drafted by the various small groups at the meeting and concluded that COSPAR should only assume responsibility for specifying P and for determining the anticipated number of missions launched by each member to a particular planet during periods of unmanned exploration. On the basis of the data described above, each member should also determine $P(C_i)$, $P(_j')$ and $P(C_j'')$ for flights by means of a conservative approximation similar to that in equation (2).

Just prior to the COSPAR meeting, Horowitz et al. (1967) published an article in *Science* criticizing the 1964 COSPAR resolution and its underlying assumptions as they apply to Mars. The authors stated that the COSPAR constraints were unnecessarily severe, not because of any deficiencies in the mathematical model (Sagan and Coleman), but rather as a consequence of unrealistic physical and biological assumptions (*Science*, 1967, 155:1504).

Specifically, the belief that eolian erosion on Mars can effect the release of spores trapped in the interior of solids in periods of time that are short compared with the time scale of the unmanned space program is unsupported by either observation or theory. On the contrary, the analysis suggests that rates of eolian erosion on Mars are very low. Similarly, present knowledge of the Martian environment opposes the view that terrestrial microorganisms would readily contaminate the planet. The combination of dryness, lack of oxygen, and high ultraviolet flux makes the surface of Mars peculiarly unsuitable for the multiplication of terrestrial organisms. Recent studies give little support to the proposal that significant areas of geothermal activity exist on Mars.

On the basis of this evidence, Horowitz et al. suggested a substantial relaxation of the COSPAR standards; they did not think that such change would compromise the biological state of Mars to any significant degree.

They emphasized the necessity of making a distinction between terrestrial organisms trapped in solids and those on the exposed surfaces of a landed spacecraft. The authors pointed out that surface sterility is an unconditional requirement, i.e., its rationale does not depend on the Martian environment. On the other hand, sterilization of the interior of solids, at the stringent COSPAR-recommended level, stems from the assumption that trapped organisms constitute a contamination hazard. Horowitz et al. felt this to be an unjustified position, and considered the need for a high degree of interior sterility doubtful.

In a subsequent issue of *Science*, Bond et al. (1967) criticized a number of points made by Horowitz et al. They stated that the American Institute of Biological Sciences Spacecraft Sterilization Advisory Committee of NASA had considered many of the questions raised by Horowitz et al. during the previous year and a half and, as a result, had developed a dry heat sterilization cycle which met COSPAR requirements and was compatible with current spacecraft engineering and design. They indicated (*Science*, 1967, Vol. 156, p. 1436):

> Horowitz's call to lower the standards is not based on any more specific data than was used for the COSPAR premise. The prime difference is that the COSPAR recommendations have taken a quantitative form in a simple model, while Horowitz's suppositions are less clearly formulated.

Bond et al. also suggested that it is more important to achieve a better understanding of sterilization procedures than to relax COSPAR standards. They advocated more precise sterilization criteria in terms of time and temperature in order to minimize the spacecraft's reliability degradation while, at the same time, meeting the sterility probability standard. The AIBS committee, in the authors' opinion, had already made progress toward this goal.

The authors were also critical of Horowitz because he did not specify a criterion to be met, nor provide a more workable probability. They believed that he should define such problems as the microbial parameter to be permitted, the cleanliness standards for his experiments, and the thermal tolerance of his equipment.

Horowitz (1967) replied to these criticisms in the same issue of *Science*. He stated that the conclusions reached in his earlier article were based on evidence not available when the COSPAR resolution and constraints were adopted in 1964. He restated the questionable validity of the assumptions underlying sterilization policy in light of more recently acquired knowledge of Mars. Thus, he felt that the AIBS committee's statement that his "conclusions were not based on any more specific data than (were) used for the COSPAR premise" was incomprehensible, as was their declaration that "reduction of COSPAR probability restraints is of lesser importance than a better understanding of sterilizing

procedures" (*Science*, 1967, Vol. 156, p. 1436). He felt establishment of a sound policy to be as important as the pursuit of technology for implementing that policy. Horowitz emphasized that, contrary to the committee's assertion, he did not reject the 10^{-3} probability. He accepted the value, but contended that it could be met without resorting to extreme sterilization procedures.

In the same issue of *Science* carrying the original Horowitz et al. article, a comparison report by Murray et al. (1967) examined the same problem from a different point of view. These authors were concerned with the similarity between U.S. and Soviet policies and practices with regard to planetary contamination and the possibility that viable terrestrial organisms had already contaminated Venus and Mars because of these practices. Murray et al. indicated the wide differences between U.S. and Soviet policies toward the COSPAR constraints. Regardless of the resulting difficulties and cost, the U.S. adopted a policy of strict interpretation of the COSPAR agreement, whereas the U.S.S.R. took a more lenient position of partial sterilization procedures and a modest risk of unintentional impact on the planets by various elements of the spacecraft system. According to the authors (*Science*, 1967, Vol. 156, p. 1505),

> Soviet practice has already led to the transfer to Venus, and probably to Mars, of a considerable number of viable terrestrial micro-organisms. Thus, both the COSPAR recommendations and current U.S. planetary quarantine policy should be reviewed and modified to reflect the probability of such transfer.

COSPAR RESOLUTION AND SUBSEQUENT CRITERIA

The criteria adopted by COSPAR in the 1964 resolution were adequate during the initial phases of the planetary quarantine program, but a number of problems became apparent when attempts were made to use these constraints with later interplanetary missions (Light et al., 1967). The more current space efforts have become increasingly complex, with a comparable multiplication of contamination sources.

Light et al. (1967) attempted to formulate a general set of standards for unmanned Martian missions based upon simple but conservative assumptions. They accepted the 1964 COSPAR resolution as a basic measure of commitment (Light et al., 1967, p. 13).

> The planetary quarantine policy shall require 99.9% confidence that the unmanned exploration of Mars will not contaminate the planet with terrestrial organisms. In other terms, the allowable probability of contamination from the entire unmanned exploratory program shall be no greater than 10^{-3}.

With this as a basic premise, they derived constraints for each unmanned mission and its sources of contamination using the following definitions:

P the probability of contamination in the total program

Q the probability of no contamination in the total program

N_l the number of landers in the total program. For the purposes of this paper, a lander is defined as a vehicle designed for landing on the planetary surface or penetrating the planetary atmosphere and is assumed to have undergone a sterilization process

N_u the number of unsterile spacecraft in the total program

P_{li} the probability of contamination originating from the *ith* lander

P_{ui} the probability of contamination originating from the *ith* unsterile spacecraft

P_l the probability of contamination originating from a lander (assumed equal for all landers)

P_u the probability of contamination originating from an unsterile spacecraft (assumed equal for all unsterile spacecraft)

P_{ua} the probability of contamination originating from the accidental impact of an unsterile (highly contaminated) vehicle or any highly contaminated part thereof

P_{uo} the probability of contamination originating from all other sources of contamination associated with an unsterile vehicle (that is, other than an accidental impact)

$R_{\text{subscript}}$ the probability of the release of one or more viable organisms on the planet by the source of contamination described by the subscript ("*l*" or "*ua*" or "*uo*" will be the subscripts)

$G_{\text{subscript}}$ the conditional probability that organisms released by the contamination source (described by the subscript) will survive, grow, and spread such that the planet is biologically infected

The following equation is designated as the probability of contamination in the total program of unmanned missions:

$$P=1-Q=1-\left[\prod_{i=1}^{N_l}(1-P_{li})\right]\left[\prod_{i=1}^{N_u}(1-P_{ui})\right] \tag{1}$$

Inasmuch as the more recent constraints require that P_{li} and P_{ui} be very small, the products of the two are negligible. Therefore:

$$P=\sum_{i=1}^{N_l}P_{li}+\sum_{i=1}^{N_u}P_{ui} \tag{2}$$

Light et al. assume that all the P_{li} are equal, and all the P_{ui} are equal, and then drop the summation sign and i subscripts, giving

$$P = N_l P_l + N_u P_u \tag{3}$$

The term in equation (3) that indicates the probability of contamination from unsterile spacecraft is expanded to include the distinction between two general classes of contamination sources: (a) those caused by accidental impact of a highly contaminated vehicle or any of its parts and (b) all other contamination sources from an unsterile vehicle. The authors then obtain the expression

$$P = N_l P_l + N_u P_{ua} + N_u P_{uo} \tag{4}$$

The contamination probability from any of the sources outlined above can represent the probability that one or more terrestrial micro-organisms will be released on the planet and the conditional probability that they will survive, grow, and spread, contaminating the planet. Thus, for the contamination source, Light et al. express

$$P_j = R_j G_j \tag{5}$$

Substituting into equation (4), they arrive at

$$P = N_l R_l G_l + N_u R_{ua} G_{ua} + N_u R_{uo} G_{uo} \tag{6}$$

Since the planetary quarantine policy requires a 99.9 percent level of confidence that the total unmanned Martian exploration program will not contaminate the planet, the primary equation on which such policy should be based is

$$P = N_l R_l G_l + N_u R_{ua} G_{ua} + N_u R_{uo} G_{uo} \leq 10^{-3} \tag{7}$$

The acceptable ranges of probabilities of the release of viable micro-organisms on Mars are given by the evaluation of the N and G constants. Finally, an acceptable planetary quarantine policy will consist of the satisfaction of equation (7) with specific values of the R's within these ranges.

In a Policy Directive dated September 6, 1967, NASA affirmed its Policy (NASA, 1967b, p. 1):

> The basic probability of one in a thousand (1×10^{-3}) that the planets of interest will be contaminated shall be used as the guiding criterion during the period of biological exploration of Mars, Venus, Mercury, Jupiter, and other planets or their satellites that are deemed important for the exploration of life, life precursors, or remnants thereof.

At approximately the same time, NASA revised its planetary quarantine plan for the Voyager Project. Until more detailed quarantine criteria

could be established for Mars, NASA outlined the contamination allocation (NASA, 1967, p. 5):

(a) For each sterilized capsule, 10^{-6}. (b) For each unsterilized spacecraft . . . 3×10^{-5}. (c) For viable organisms released on Mars, the probability of survival and growth shall be considered on 10^{-3}.

PLANETARY QUARANTINE REQUIREMENTS

Wiederkehr (1967) outlined "An Operational Model for Planetary Quarantine Requirements" for the 1965–1985 period of unmanned Martian exploration. During the interval, N number of launches from the U.S. and U.S.S.R. were planned, using different types of vehicles and thus presenting different contamination probabilities. Wiederkehr numbers these launches chronologically from 1 to N, with p_i representing the probability that Mars will be contaminated by the i^{th} launch, and P_c the probability that the planet will be contaminated with terrestrial organisms by at least one of these launches. Assuming that the contamination events (launches) are independent, he states the following relationship:

$$1 - P_c = \prod_{i=1}^{N} (1 - p_i) \tag{1}$$

This is based on the theory that in order to not contaminate Mars, every individual launch must not contaminate the planet.

The aim of the sterilization program, according to Wiederkehr, is to make the p_i's small enough so that P_c stays under a stated small value such as 0.001, or that $1 - P_c$ exceeds a value close to unity (0.999). He points out that, following equation (1), $p_i < P_c$ and, thus, P_c and all of the p_i's are small relative to unity. He then reduces equation (1) to a simple expression. From the logarithms of this equation, he obtains

$$\log_e (1 - P_c) = \sum_{i=1}^{N} \log_e (1 - p_i) \tag{2}$$

By using Taylor's formula (with remainder) for $\log (1 - p_i)$ expanded about the point $p_i = 0$, Wiederkehr arrives at

$$\log (1 - p_i) = -p_i + R_{li} \tag{3}$$

where

$$R_{1i} = -\frac{\phi_i 2}{2}, \qquad 0 < \phi_i < p_i \tag{4}$$

In the same way, Taylor's formula is used for $\log (1-P_c)$:

$$\log (1-P_c) = -P_c + R_{1c} \tag{5}$$

$$R_{1c} = -\frac{\phi_c^2}{2}, \qquad 0 \leq \phi_c < P_c \tag{6}$$

Wiederkehr then substitutes equations (3), (4), (5), and (6) into (2), to produce

$$P_c = \sum_{i=1}^{N} p_i + \epsilon \tag{7}$$

where

$$\epsilon = \frac{1}{2} \sum_{i=1}^{N} \phi_i^2 - \frac{1}{2} \phi_c^2 \tag{8}$$

He then summarizes the inequalities outlined above:

$$0 < \phi_i < p_i \leq P_c \tag{9}$$

$$0 < \phi_c < P_c \tag{10}$$

Substituting equations (9) and (10) into (8), he obtains

$$-\frac{P_c^2}{2} < \epsilon < \frac{NP_c^2}{2} \tag{11}$$

When $N = 20$ and $P_c = 10^{-3}$, then, following equation (11), $\epsilon < 10^{-5}$. Thus, the error produced by ignoring ϵ in equation (7) is negligible, and the author uses equation (12) below as an approximation of equations (7) and (8).

$$P_c = \sum_{i=1}^{N} p_i \tag{12}$$

Wiederkehr affirms that by utilizing an average p_i, one can evaluate

the relative error in specifying p_i. The former is termed $\bar{p}_i$, and if $\Delta\bar{p}_i$ is the error, then

$$\frac{\Delta\bar{p}_i}{\bar{p}_i} = \frac{\frac{P_c}{N} - \frac{P_c - \epsilon}{N}}{\frac{P_c - \epsilon}{N}} = \frac{\epsilon}{P_c - \epsilon} \cong \frac{\epsilon}{P_c} = \frac{NP_c}{2} \tag{12a}$$

The author then states the following (Wiederkehr, 1967, p. A–3):

. . . in the previous example, for $P_c = 10^{-3}$ and letting $N = 20$, there would be at most a 1% error in specifying p_i due to the approximation. If the number of launches were to be increased to $N = 100$, the error would be less than 5%, e.g., the specified $\bar{p}_i$ would be 1×10^{-5} while the "exact" value would fall between 1×10^{-5} and 1.05×10^{-5}. This is clearly an insignificant difference in relation to the basis for choosing $P_c = 10^{-3}$.

Thus far, Wiederkehr has treated each launch as separate from all of the others. However, in order to categorize them by such things as nationality and type of vehicle and then arrive at aggregate probabilities for each category, he divides N launches into k categories, with p_{ij} the probability of contaminating Mars by the i^{th} launch of the j^{th} category and n_j the number of launches in the j^{th} category. Equation (12) is then rewritten as

$$P_c = \sum_{j=1}^{k} \sum_{i=1}^{n_j} p_{ij} \tag{13}$$

or

$$P_c = n_1\bar{p}_1 + n_2\bar{p}_2 + \ldots + n_k\bar{p}_k \tag{14}$$

where

$$\bar{p}_j \equiv \frac{1}{n_j} \sum_{j=1}^{n_j} p_{ij} \tag{15}$$

In equation (15), the average probability of each launch in category j contaminating Mars is $\bar{p}_j$. As an example, Wiederkehr uses the four categories in Table 8.

Applying equation (14) then gives

$$P_c = n_1\bar{p}_1 + n_2\bar{p}_2 + n_3\bar{p}_3 + n_4\bar{p}_4 \tag{16}$$

Table 8 *Contamination Probabilities of Launches by Category and Number (after Wiederkehr, 1967, p. A–5).*

j	Categories	Average Probability of Contamination	Number of Launches
1	U.S. landers	$\bar{p}_1$	n_1
2	U.S. non-landers	$\bar{p}_2$	n_2
3	Russian landers	$\bar{p}_3$	n_3
4	Russian non-landers	$\bar{p}_4$	n_4

In the analysis above, it was assumed that the total number of launches (N) and the number in each category (n_j) were known. However, since they are not known and must be predicted, Wiederkehr considers them random variables (Wiederkehr, 1967, p. A–5).

P_c as given by (14) is actually a conditional probability, the condition being that the number of launches in the j^{th} category is n_j for $j=1, 2, \ldots, k$. To remove this condition, it is necessary to average over all possible values of the n_j's.

When the $\bar{p}_i$'s are assumed to be independent of the n_j's and approximately constant, and when equation (14) is averaged over all of the possible values of the n_j's, the following equation results:

$$\bar{P}_c = \bar{n}_1\bar{p}_1 + \bar{n}_2\bar{p}_2 + \ldots + \bar{n}_k\bar{p}_k \tag{17}$$

where

$\bar{P}_c$ the average (expected) value of P_c
$\bar{P}_i$ the average (expected) value of p_i, $i=1, 2, \ldots, k$.

In order to arrive at the 1966 COSPAR model from equation (17), Wiederkehr outlines three additional steps. First, using only two categories, landers and nonlanders (unsterilized vehicles), he expresses

$$P_c = n_L p_L + n_U p_U \tag{18}$$

where

n_L the expected number of landers
p_L the average probability that a lander contaminates Mars
n_U the expected number of unsterilized (nonlander) vehicles
p_U the average probability that an unsterilized vehicle contaminates Mars

The second step involves a lander that contaminates Mars. This necessitates the following:

1. At least one viable organism survives the sterilization treatment and arrives at Mars on the lander.
2. The viable organisms which survive the sterilization treatment and arrive at Mars are released.
3. The viable organisms which survive the sterilization treatment, arrive at Mars, and are released also grow and spread.

The probabilities of these three events are symbolized by p_N, p_R, and p_G, so that

$$p_L = p_N \cdot p_R \cdot p_G \cdot \tag{19}$$

Finally, the contamination of Mars by an unsterilized vehicle requires that none of the possible contamination sources from such a vehicle, e.g., accidental impact or ejecta from altitude control, comprise the contaminants. Wiederkehr's logic is similar to that used for equation (12), so that the contamination probability for independent sources of contamination is the sum of the probabilities of contamination for each of the sources. He goes on to state that for a specific source to contaminate the planet, the following are required:

1. The viable organisms due to source i are transferred to the surface of Mars.
2. The viable organisms transferred to Mars from source i are released.
3. The viable organisms transferred to Mars from source i and released also grow and spread.

The probabilities of these three events are represented by $(p'_T)_i$, $(p'_R)_i$, and $(p'_G)_i$. Then,

$$P_U = \sum_i (p'_T)_i (p'_R)_i (p'_G)_i \tag{20}$$

Wiederkehr concludes that by substituting equations (19) and (20) into equation (18), the 1966 COSPAR model can be derived:

$$P_c = n_L p_N p_R p_G + \sum_i{}' (p'_T)_i (p'_R)_i (p'_G)_i \tag{21}$$

POLICIES ON CONTAMINATION CONTROL

At the 1968 COSPAR meeting in Tokyo, the COSPAR Executive Council proposed a resolution later enacted by the plenary body as Resolution 21. The council expressed concern with the effectiveness of the measures being taken to prevent space probes from contaminating Mars and the

other planets. It was observed in the resolution that the Panel on Standards of Space Probe Sterilization had not been active recently, and COSPAR requested that the Consultative Group on Potentially Harmful Effects of Space Experiments convene to consider this problem, as well as the possibility of reactivating the Panel on Standards for Space Probe Sterilization as the Panel on Planetary Quarantine.

In the March 15, 1968, issue of *Science* which carried an article by Sagan et al., the authors attempted to clarify their positions on planetary quarantine policy and the contamination of Mars. They were particularly concerned with the articles by Horowitz et al. (1967) and Murray et al. (1967), published earlier in *Science*. These two reports concluded that the COSPAR constraints could be significantly relaxed from the 1×10^{-4} probability of a single viable organism's being aboard any spacecraft to be landed on Mars and the 3×10^{-5} probability of accidental impact by an unsterilized flyby or orbiter during the period of exploration. Sagan et al. are critical of this position and, on the basis of their belief that there is a significant chance of contaminating Mars, recommend that spacecraft be carefully sterilized. But Horowitz et al., citing evidence derived from *Mariner 4* and Earth-bound observations, including data which they believe do not support the contention that all microorganisms aboard a lander will have access to the Martian surface, suggest that it would be feasible to significantly increase the allowable microbial load per spacecraft. After examining this same evidence, Sagan et al. maintain that their position advocating the careful sterilization of Mars-bound spacecraft is justified.

One of the important points Sagan et al. raise (which they claim Horowitz et al. appear to have missed) is the difference between the conclusions drawn by COSPAR and Sagan in regard to the parameter σ: "The COSPAR recommendations refer to the 'probability that a single viable organism be *aboard* any vehicle intended for planetary landing.'" (Sagan et al., 1968, p. 1192). Sagan et al. define σ as "the mean number of viable micro-organisms per capsule which are distributed outside the capsule, on the Martian *surface*" (Sagan, et al., 1968, p. 1192). They point out that the difference refers to the mean probability of a contained micro-organism's being released and that COSPAR decisions, as well as their own, were influenced by their lack of knowledge of release over a period of decades. Horowitz et al. think that surface sterilization procedures are sufficient, since the probability of release is very small. Sagan et al. conclude that the primary difference between the two positions is that they (Sagan et al.) are reluctant to "consider a compound risk that may be small by conventional standards—say, 10^{-2}—as equivalent to zero when the stakes are very high" (Sagan et al., 1968, p. 1192).

Sagan et al. go on to discuss some of the problems associated with

analyzing the release mechanisms of organisms following a crash landing or the successful landing of an intact spacecraft. Information on phenomena such as fragmentation at various velocities is greatly needed. Horowitz has stated that if fragmentation tends to take place along identifiable fracture planes, then surface sterilization of these planes will be quite effective. However, as Sagan et al. observe, "there are almost no data available on fracture modes for various scenarios of mission failure" (Sagan et al., 1968, p. 1192).

Horowitz et al. also maintain that eolian erosion is minimal on Mars for long periods (decades), estimating that the maximum wind velocity required for rolling and saltation is 145 to 250 kilometers per hour. Since calculations by Leovy (cited in Sagan et al.) put the highest velocity as 80 to 160 kilometers per hour, Horowitz et al. conclude that these are probably too low to induce grain movement. Nevertheless, Sagan et al. consider both estimates so uncertain that they may be considered identical. They believe that dust devils with large vortex velocities are present on the Martian surface and that it is unlikely that all or most are produced by meteorite impacts.

Sagan et al. are also critical of the acceptance by Horowitz et al. of eolian erosion rates (less than 1 mm. every few decades) in lucite for terrestrial deserts. They are particularly critical of the extrapolation to the erosion of exterior components of a spacecraft on the Martian surface. Such an assumption is thought to be uncertain to several orders of magnitude when the present state of our knowledge about eolian erosion rates on Mars is so inadequate. Sagan et al. note that many components of a Mars landing vehicle have crevices some millimeters deep, requiring sterilization down to that depth.

The authors also classify the values of the parameters selected in the Sagan-Coleman model as averages representing many missions. Their immediate concern is with the parameters for the first landing missions, with the probability of an accidental crash landing not less than 0–1, and possibly as small as 0.5. But, they state that even this number presented in arguments by Horowitz et al. fails to take into account the large range of possibilities between complete failure due to crash landing and eolian erosion down to a depth of some millimeters. Sagan et al. illustrate this point by showing that $1 - P_t$ is not the probability of a catastrophic crash landing as stated by Horowitz et al. Instead, it refers to the chance that some fraction of the experiments in the lander will not function as planned. P_t represents the probability of complete engineering and scientific success. The authors caution that the possibility must be considered that the lander may suffer partial damage, allowing micro-organisms from only some parts of the spacecraft to reach Mars. A number of other potential spacecraft fractionation

mechanisms are discussed. The authors feel that until more information is available, the possibility of contamination due to such sources requires sterilization of spacecraft interiors.

Possibility of Microbial Growth on Mars Another important issue in this controversy centers around the fact that Sagan et al. believe that the geothermal activity on Mars indicates the presence of water and local high temperatures which would facilitate the growth of terrestrial-type micro-organisms. On the other hand, Horowitz et al. do not accept such possibilities and maintain that the planet is undifferentiated and geologically inactive. Sagan et al. state further that Mars probably has a subsurface permafrost layer, with loosely bound or adsorbed water in the surface material, and that the water would be released to the surface by geothermal activity. It is also possible that the permafrost layer is sometimes breached by the impact of meteorites. They also cite evidence suggesting that Mars is probably differentiated.

The authors assert that lifetime of liquid water on Mars is a more serious question and that salt deposits will lower the eutectic point—in many cases by several 10's of degrees. Sagan et al. also feel that there may be frequent briny pools on Mars. While Horowitz et al. imply that all halophiles are aerobes, Sagan et al. believe that this must be an artifact of the experimental conditions and that not much effort has been put into finding anaerobic halophiles. Sagan et al. conclude that the available evidence strongly suggests that some terrestrial micro-organisms will grow in the Martian environment. This leads to the suggestion that the 10^{-2} probability that an organism deposited on the surface of the planet will grow and contaminate it may mean that 10^{-2} is too low rather than too high.

Sagan et al. also comment on an article by Murray et al. printed in the same issue of *Science* as the one by Horowitz et al. (discussed above). Murray et al. held that the sterilization standards for American vehicles could be lowered considerably. They gave the following reasons. The U.S.S.R. program is not failsafe in the same way as that of the U.S., since the latter's flybys are deflected away from the planet during midcourse maneuvers; *Zond II* may have impacted Mars; and Soviet vehicles that will impact the planet during future missions will be subjected to sterilization methods not evaluated in the West. Horowitz et al. and Murray et al. argue that there is little chance of Mars' being contaminated, and that *Zond II* probably did not contaminate the planet. But Sagan et al. contend that there is a significant probability of contaminating Mars and ask, therefore, if the points made by Murray et al. then follow (Sagan et al., 1968, p. 1195).

> Each contention of Murray et al. has some associated uncertainty, and it is not clear that any micro-organisms have landed on the Martian surface as a result of the *Zond II* mission.

The new data provided by *Mariner IV* enabled Hawrylewicz et al. (1968) to test the probability of growth of viable terrestrial microorganisms in an environment that simulated the Martian atmosphere much more accurately than had been possible previously. They concluded that on the basis of an intensive study of *S. aureus*, which is closely associated with man and can grow under anaerobic conditions, if moisture is present in the Martian environment, an organism such as this would survive and grow when released into the Martian soil. It could, then, pose a serious contamination hazard for the planet.

Hall (1968b, p. 25) points out that because of "our limited knowledge of planetary environments, the best analysis of probability of growth might be based on conservative judgment values of those factors that can be defined". Assuming that there are microenvironments on Mars in which viable terrestrial organisms (VTO's) can grow, he designates 1×10^{-1} as the probability that a VTO on a spacecraft will manage to reach such a microenvironment. A similar probability (1×10^{-1}) is postulated for a particular species (i.e., one that will reproduce) among the different VTO's on the spacecraft reaching the microenvironment. If the trauma of transition from terrestrial to Martian conditions reduces the population by 90 percent, then (Hall, 1968, p. 25)

> . . . the probability of organism survival during transition may be set at 1×10^{-1}. Also, the probability that the organisms will survive the radiation and other hazards encountered in transit from the spacecraft to the microenvironment may be estimated at 1×10^{-1}.

Hall believes that several other probabilities regarding survival and growth, each less than unity, can be estimated. He concludes that the survival and growth of VTO's on the planet is not unity, as had been thought by many, but somewhere in the range between 1×10^{-2} and 1×10^{-8}, or less.

NASA Policies In a statement before the Subcommittee on Space Science and Applications of the House of Representatives in 1968, John E. Naugle, Associate Administrator for the Space Science and Applications, NASA, reviewed some general aspects of NASA policy regarding planetary quarantine. He defined the basic objectives of the NASA Planetary Quarantine Program as

1. In the lunar exploration program, to keep contamination of spacecraft by live terrestrial organisms to a low level and to locate and identify all contamination that does reach the Moon
2. In the planetary exploration program, to prevent the transfer to the planets of terrestrial life that would change the existing planetary biota or interfere with the search for life
3. In programs involving missions returning to Earth from the Moon or planets (a) to obtain uncontaminated samples for biological analysis upon the Earth and (b) to protect the Earth's biota

from possibly disastrous effects of returned extraterrestrial life forms

Levinthal et al. (1968), in their "Relationship of Planetary Quarantine to Biological Search Strategy," attribute the COSPAR constraints to previous quantitative studies based on two propositions (Levinthal et al., 1968, p. 136).

First, that the scientific issue of detection and characterization of life was the overriding value to be considered, and, secondly, that as many as 60 missions might be ultimately needed to settle this issue.

Data from *Mariner IV* and other observations have, according to the authors, reduced the range of uncertainty of a number of the parameters involved and, as a result, there has been some controversy regarding planetary quarantine constraints for future missions. They visualize a dynamic relationship between planetary strategy and quarantine standards, with both influenced by completed explorations, future technology, and changes in exploration goals.

Levinthal et al. suggest that the most important factor bearing on the relationship between planetary quarantine and biological search strategy, insofar as the decision analysis is concerned, is the total utility of Mars. Scientific uses constitute only one aspect of this utility, but if a high value is placed on the planet's utility, then a very stringent sterilization policy should be adopted. As an example, they consider the possibility of making Mars more habitable by revising its atmosphere. This feat might require the contrivance of certain planet forms which might not survive in the presence of terrestrial contaminants (Levinthal et al., 1968, p. 142).

Thus spores could be a hazard by persisting on Mars until reengineering the planet is attempted. To evaluate this utility a complex probability analysis is needed. (They do) not wish to incur the great increases in cost that might be involved in protecting this potential value without a better estimate of the possible gains.

Two other variables that should be considered in this relationship are the probability of survival of terrestrial micro-organisms on Mars and their propagation. This is particularly important in view of recent evidence and suggestions that quarantine standards be relaxed. In addition, Levinthal et al. suggest that any decisions to be made on quarantine procedures should be preceded by an explicit statement concerning the probability of life on the planet. This, in turn, involves the question of the resemblance between Mars and terrestrial biota, a question having significant implications for the problem of contamination as a source of confusion.

According to the authors (Levinthal et al., 1968, p. 145):

Mission policy should be conservative, involving only initial probabilities with narrow intervals. The *Mariner IV* mission showed that a probability limit for accidental planetary

impact by an unsterilized flyby of 3×10^{-5} or less does not preclude carrying out useful missions. . . . Initial policy should be limited to configurations involving flybys, orbiters and terminally heat sterilized landers and combinations of these which meet at least as stringent sterilization standards as presently recommended by COSPAR.

Reynolds developed a relatively simple and basic mathematical model (Hall, 1968c, pp. 4–5).

The probability of contaminating the planet is equal to the sum of all possible contaminating events, i.e., each evaluated by the probability of transfer to the planet (P_T), the probability of release from the spacecraft (P_R), and the probability of growth and spread (P_G).

The model is described by the following equation:

$$P_c = \sum^{i} (P_T)_i \cdot (P_R)_i \cdot (P_G)_i$$

P_c: probability that the planet will be contaminated

$\sum^{i}$: sum of each of the possible contaminating events

$(P_T)_i$: probability of transfer

$(P_R)_i$: probability of release

$(P_G)_i$: probability of growth and spreading

where

i distinct, independent sources of contamination

Hall believes that by summarizing the pertinent planetary quarantine relationships of the Schalkowsky and Cooley model discussed at COSPAR, the result might be a desirable expansion.

Model for Need to Define Contamination Trauth recognizes the considerable degree of uncertainty inherent in any program of planetary exploration which, in turn (Trauth, 1968, p. 135),

. . . leads to possible uncertainty in the time period in which planetary quarantine is desirable, to possible uncertainty in the total number of missions to be launched in the vicinity of any given planet, and indeed, to possible uncertainty in the meaning of the word "contamination."

In order to make "possible the derivation of mission noncontamination requirements without a priori knowledge of either the time period in which planetary quarantine is to be observed or the total number of missions to be used in exploring the planet being quarantined" (Trauth, 1968, p. 135). Trauth developed a model which permits several general observations concerning the need for precisely defining "contamination."

Trauth designates the term $\hat{P}_{N.C.}$ as the minimum acceptable probability of not contaminating a planet during a specific time period or T. These two parameters and the word "contamination" are regarded as variables for any particular planet. The program objective, then, is seen

as $(1-\hat{P}_{N.C.})$, i.e., the "probability that any planet deemed important for the study of extraterrestrial life, or precursors or remnants thereof, be contaminated during the next T years shall not exceed" (Trauth, 1968, p. 136) this value.

By using n as the total number of missions, and $n(T)$ as the total number of missions used to explore the planet during the time period, Trauth is able to state a simple model in which $\hat{P}_{N.C.}$ is expressed in terms of $n(T)$ and $\hat{P}_c(n(T))$, the highest contamination probability that can be accepted for the planet from any of the $n(T)$ spacecraft:

$$\hat{P}_{N.C.} = \{1-\hat{P}_c[n(T)]\}^{n(T)} \tag{1}$$

He assumes that contamination from one mission is independent of that from other missions. If $P_C^{(i)}$, which represents the contamination probability from the i^{th} mission, satisfies the inequality $P_C^{(i)} \leq \hat{P}_C(n(T))$ for all $i = 1, 2, \ldots, n(T)$, then $P_{N.C.}(n(T))$, the probability that the planet in question will not be contaminated by $n(T)$ missions during the time period T, is said to satisfy the program objective, that is, $P_{N.C.}(n(T)) \geq \hat{P}_{N.C.}$.

Trauth writes that the Sagan-Coleman model was the first attempt at using an existing uncertainty in a quarantine requirements model. However, this model, as well as those which evolved in the next few years (i.e., those developed by Schalkowsky, Cornell, and the model used in the 1966 COSPAR discussions) "did not resolve the problem of incorporating the many forms of uncertainty into the derivation of mission requirements" (Trauth, 1968, p. 138). The COSPAR model is basically very similar to equation (1), except that an upper bound for the total number of missions is used in place of $n(T)$, inferring that an upper bound for T is known. This implies, as Trauth shows, a priori knowledge about the time period T and the total number of missions. "The difficulty one can encounter in this approach is that the more uncertainty there is, the higher the upper bound should be; while at the same time, the higher the upper bound becomes, the more stringent the mission requirements become" (Trauth, 1968, p. 138). Trauth goes on to present a model in which mission requirements can be derived without making any assumption of a priori knowledge concerning T or $n(T)$.

In developing his multistage decision model, Trauth retains terms similar to $\hat{P}_C(n(T))$ in equation (1), but in a somewhat different form because of the uncertainty about T and $n(T)$. With N_1 as the total number of missions launched in the vicinity of a specific planet, and if there are not more than N_1 missions, then

$$\hat{P}_{N.C.} = (1-\hat{P}_1)^{N_1} \tag{2}$$

This equation produces a requirement on the contamination probability, P_1, for each of the missions, N_1, so that $P_1 \leq \hat{P}_1$ (Trauth, 1968, p. 139).

That is, if no more than N_1 missions are launched, and if $P_1 \leq \hat{P}_1$ for each mission launched, then the probability that the planet is not contaminated during the desired time period, denoted $P_{N.C.}$, satisfies the inequality $P_{N.C.} \geq \hat{P}_{N.C.}$, which, in essence, represents the attainment of the program objective.

Assuming that after M_1 of the estimated N_1 missions are launched it is determined that N_1 is incorrect, an estimate of N_2 additional missions will be required rather than $N_1 - M_1$ missions. However, each of the N_2 missions must meet a different contamination requirement than the one met by the first M_1 missions. Trauth determines this new requirement from the following:

$$\hat{P}_{N.C.} = (1-\hat{P}_1)^{M_1}(1-\hat{P}_2)^{N_2} \tag{3}$$

Thus, a requirement assumed to be attained on the initial M_1 missions already launched is defined by $\hat{P}_1$, producing P_2, which is the contamination probability for any of the remaining N_2 missions:

$$P_2 \leq \hat{P}_2$$

Trauth points out that the only unknown in equation (3) is $\hat{P}_2$, if it is assumed that $\hat{P}_{N.C.}$, N_1, N_2, and M_1 are given. Therefore, $\hat{P}_2$ can be derived when $M_1 < N_1$. "If, then, $P_2 \leq \hat{P}_2$ for each of the remaining N_2 missions and $P_1 \leq \hat{P}_1$ for the M_1 missions already launched, one again has $P_{N.C.} \geq \hat{P}_{N.C.}$; implying the attainment of the program objective" (Trauth, 1968, p. 140).

Carrying the logic further, Trauth writes that after M_2 of the estimated additional N_2 missions have been launched ($M_2 < N_2$) and the estimate N_2 is thought to be incorrect, it is estimated that N_3 more missions will be required. The estimated total number of missions would then be $M_1 + M_2 + N_2$, with $M_1 + M_2$ already launched, and an estimated N_3 additional missions needed. He then derives a new requirement on the contamination probability, P_3, for any of the remaining N_3 missions from

$$\hat{P}_{N.C.} = (1-\hat{P}_1)^{M_1}(1-\hat{P}_2)^{M_2}(1-\hat{P}_3)^{N_3} \tag{4}$$

That is $P_3 \leq \hat{P}_3$. Trauth states that this is possible because $\hat{P}_1$ and $\hat{P}_2$ are known from the solutions to equations (2) and (3), and that equation (4) can always be solved if $M_1 < N_1$ and $M_2 < N_2$.

Trauth then defines the following terms (Trauth, 1968, pp. 140–141):

N_1 the first estimate of the total number of missions to

	be launched in the vicinity of the planet in question
M_1	the number of these N_1 missions launched prior to a reestimation of the total number of missions required
$M_1 + N_2$	the second estimate of the total number of missions to be launched in the vicinity of the planet in question
$M_1 + M_2$	the number of these $M_1 + N_2$ missions launched prior to a third estimate of the number of missions required
$\left(\sum_{j=1}^{k-1} M_j\right) + N_k$	the *kth* estimate of the total number of missions to be launched in the vicinity of the planet in question
$\left(\sum_{j=1}^{k-1} M_j\right) + M_k$	the number of these missions launched prior to the $(k+1)$st estimate of the number of missions required
$\hat{P}_k$	the maximum acceptable probability of contamination from any of the last N_k missions needed to fulfill the *kth* estimate of the total number of missions required

The model is sequential, so that $\hat{P}_1$ can be obtained from equation (2). If $\hat{P}_1, \hat{P}_2, \ldots, \hat{P}_{k-1}$ are known, one can get $\hat{P}_k$ by solving the following equation:

$$(1 - \hat{P}_k)^{N_k} = \frac{\hat{P}_{N.C.}}{\prod_{j=1}^{k-1} (1 - \hat{P}_j)^{M_j}}$$

Trauth represents the contamination probability for the planet from the i^{th} mission with $P_C^{(i)}$. Then, if

$$P_C^{(i)} \text{ x} \leqslant \hat{P}_j,$$

for

$$\sum_{s=1}^{j-1} M_s < i \leqslant M_j$$

and

$$1 \leqslant j < k$$

and

$$P_c^{(i)} \leqslant \hat{P}_k,$$

for

$$\sum_{s=1}^{k-1} M_s < i \leqslant N_k$$

then the probability of not contaminating the planet during the time period will satisfy the following inequality: $P_{N.C.} \geqslant \hat{P}_{N.C.}$. This last relationship represents the achievement of the program objective, assuming that the final estimate is the k^{th} estimate of the number of missions required.

Trauth is able to include the potential dependence of $\hat{P}_{N.C.}$ upon time in the model by making the assumption that $\hat{P}_{N.C.}$ may be changed only when the required number of missions is reestimated. He replaces $\hat{P}_{N.C.}$ in equation (5) with the k^{th} estimate of $\hat{P}_{N.C.}$, shown as $\hat{P}_{N.C.}^{(k)}$. The k^{th} mission-oriented requirement, $\hat{P}_k$, is then obtained from

$$(1-\hat{P}_k)_{N_k} = \frac{P_{N.C.}^{(k)}}{\prod_{j=1}^{k-1} (1-\hat{P}_j)^{Mj}} \tag{6}$$

for $k > 1$. $\hat{P}_1$ is obtained from equation (2) as before. Trauth asserts that, in this form, the existence of a nonzero solution for $\hat{P}_k$ depends upon the magnitude of $P_{N.C.}^{(k)}$. That is, that there is a nonzero solution for $\hat{P}_k$ if and only if the right-hand side of equation (6) is less than 1.

If "classes" of missions are to be distinguished, e.g., sterilized vs unsterilized, then N_j is treated on a sum of numbers n_{ij}, $i=1, 2, \ldots r_j$, where the breakdown into r_j numbers indicates the distinctions. In order to take into account the possibility that the classes will change, Trauth has included the dependence of the index r upon the estimated number j. Equation (6) is then replaced by equation (7):

$$\prod_{i=1}^{r_k} (1-\hat{P}_{ik})^{nik} = \frac{P_{N.C.}^{(k)}}{\prod_{j=1}^{k-1} \left\{ \prod_{i=1}^{r_j} (1-\hat{P}_{ij})^{mij} \right\}} \tag{7}$$

The highest acceptable probability of planetary contamination from any mission of the i^{th} class after the j^{th} estimate of the total missions in that

class is $\hat{P}_{ij}$, and $M_j = \sum_{i=1}^{r_j} m_{ij}$. The number of the n_{ij} estimated missions launched before the $(j+1)$st estimate of the total number of missions needed in each of the r_j+1 classes is designated m_{ij}. Using this method, Trauth replaces equation (2) with

$$\prod_{i=1}^{r_1} (1-\hat{P}_{i1})^{n_{i1}} = P_{N.C.}^{(1)} \tag{8}$$

The author then states the following (Trauth, 1968, p. 142):

Finally, to obtain the general model, it is observed that the requirements, $\hat{P}_{ij}$, appearing in equation (7) may be replaced by a posteriori estimates of the actual probability of contamination from m_{ij} missions of the i^{th} class launched as a result of the j^{th} estimate. For example, after launching m_{i1} missions, $i = 1, 2, \ldots, r_1$, in the first stage, the probability that the planet in question *is not* contaminated from vehicles of the i^{th} class is not $(1-\hat{P}_{i1})^{m_{i1}}$, but rather $\prod_{s=1}^{m_{i1}} [1-\tilde{P}_{i1}^{(s)}]$, where $\tilde{P}_{i1}^{(s)}$ is the *actual* probability of contamination of the planet from the s^{th} mission of the i^{th} class as *judged* on the basis of the knowledge available after the missions have been launched.

Trauth shows that the $\tilde{P}_{i1}^{(s)}$ may differ from $\hat{P}_{i1}$ because the means of achieving the requirement $\hat{P}_{i1}$ may, during or after the time they are used, result in a mission contamination probability considerably less than that required, although there is no change in the concept of what is needed to contaminate the planet. Another difference is that there may be a change in thinking regarding what is required to contaminate a planet as a result of new evidence concerning the planet. Thus, as Trauth demonstrates, there is a possible dependence of a posteriori contamination probabilities upon time. Consequently, he uses $P_{ij}^{(s)}(t_k)$ to "denote the a posteriori probability of contamination from the s^{th} of m_{ij} missions of the i^{th} class, j^{th} stage, as judged at the time, t_k, of the k^{th} estimate" (Trauth, 1968, p. 143).

On this basis, Trauth's general model takes the form

$$\left.\begin{aligned} &\prod_{i=1}^{r_1} (1-\hat{P}_{il})^{n_{i1}} = P_{N.C.}^{(1)}, \\ &\text{and for } k>1, \\ &\prod_{i=1}^{r_k} (1-\hat{P}_{ik})_{nik} = \frac{P_{N.C.}^{(k)}}{\prod_{j=1}^{k-1} \left\{ \prod_{i=1}^{r_j} \left[\prod_{s=1}^{m_{ij}} (1-P_{ij}^{(s)}(t_k)) \right] \right\}} \end{aligned}\right\} \tag{9}$$

Trauth concludes that the above model seems to provide a means of deriving mission noncontamination requirements from the program objective with minimal a priori knowledge of the exploration program to which the program objective applies. He feels that mission requirements may be derived by

1. Estimating the number of missions of each class to be flown
2. Correcting for inaccuracies in estimates before all the previously estimated vehicles of a given class are launched

Finally, Trauth states (Trauth, 1968, pp. 143–144):

> At no stage, save possibly the last decision stage, need one make a correct estimate. In fact, *no* estimate need be correct if the last estimate is too large. Hence, the general goal of providing a means of deriving mission non-contamination requirements from the Program Objective using a minimal amount of *a priori* knowledge about the exploration program, seems in theory, to have been achieved. It also provides for using any such knowledge available, as well as any knowledge gained during the course of exploration.

COSPAR OBJECTIVES FOR PLANETARY QUARANTINE

Both the 12th Plenary Session of COSPAR and the 10th International Space Science Symposium were held in Prague, May 11–24, 1969. COSPAR reaffirmed the basic objective for the planetary quarantine of Mars and other planets as a probability of no more than 1×10^{-3} for contamination during the period of biological exploration.

The period was assumed to be 20 years, extending through December 31, 1988, and to include approximately 100 missions. It was stated that no nation should use up more than 15 percent of the total contamination risk during the initial 5 years of exploration. This was based on COSPAR Resolutions 26.5 and 26.7 (1964), the 1966 and 1967 Reports of the Consultative Group on Potentially Harmful Effects of Space Experiments, and the work of the Panel on Standards for Space Probe Sterilization (whose title changed to the Panel on Planetary Quarantine).

In order to achieve this objective, COSPAR recommended in its Decision No. 16 that members submit specified information not more than 3 months after launch, describing sterilization procedures and computations. It was suggested that the reports include at least the following (COSPAR Decision 16, 1969):

1. The mathematical model used as a basis for computing the probability of contamination. 2. The computations used in applying the model. 3. The estimated biological burden at launch and at encounter. 4. The probable composition (identification) of the biological burden. 5. Methods used to decontaminate and/or sterilize the space flight hardware. 6. Intended trajectory before and after midcourse correction. 7. Type of deflection used, bus or capsule. 8. Intended orbit parameters.

It was also suggested that the probability that viable organisms transferred to the planet's surface would grow and spread should be carefully and conservatively established.

In compliance with COSPAR Decision 16, R. W. Porter, the NAS representative to COSPAR, submitted a NASA report on the probability of the U.S. Mariner 1969 mission's contaminating Mars. The mission consisted of two identical spacecraft (*Mariner 6* and *Mariner 7*), and, in line with the 3×10^{-5} constraint in COSPAR Resolution 26.5,

"a probability of contamination P_C of 6.0×10^{-5} was established as the limit not to be exceeded by both flights or 3×10^{-5} for each launch" (Porter, 1969, p. 1). The report outlines the mission trajectory analyses and controls carried out by the Jet Propulsion Laboratory to keep the probability within this limit.

Reynolds (1969) reviews various aspects of the NASA Planetary Quarantine Program. He points out that parameters other than those set by COSPAR (1×10^{-3}) for the probability of contaminating a planet during the period of exploration and by the SSB (1×10^{-3}) for the probability of growth of viable terrestrial organisms on Mars and (1×10^{-1}) for random landings on the surface of Venus must be established for 1971 and 1973 Mars missions. The proposed parameters for planetary quarantine are shown in Table 9.

Table 9 *Proposed Parameters for Planetary Quarantine (after Reynolds, 1969, p. 4).*

Planet	P_c	P_C^*
Mars		
Surface	1×10^{-3}	1×10^{-3}
Atmosphere	(Not Considered To Be of Concern)	
Venus		
Surface	1×10^{-3}	1×10^{-6}
Atmosphere	1×10^{-3}	1×10^{-4}
Jupiter		
Surface	1×10^{-3}	1
Atmosphere	1×10^{-3}	1

*For random landing points.

During the 20-year period established for the biological exploration of Mars, there will be nine Mars opportunities, and, by a conservative estimate, 30 flyby/orbiters and 70 landers. Reynolds believes that on the basis of the planetary quarantine models that will be in use during this period, the following constraints are indicated: a $P_c = 3 \times 10^{-5}$ for each flyby/orbiter and $P_C = 1.4 \times 10^{-6}$ for each lander, or $P_C = 3 \times 10^{-5}$ for the 1971 flight and 3.14×10^{-5} for the 1973 flight. He also states that the U.S. position is that COSPAR should set only the value of P_C, and that the model parameters should be established by the launching nation.

NASA ORGANIC CONSTITUENTS DESIGN CRITERIA

The Space Science Board convened an ad hoc group of scientists on March

26, 1969, in response to a request from Orr Reynolds, Director of NASA's Bioscience Program Office. The purpose was to (Favorite, 1969, p. 1)

> . . . consider the organic constituents design criteria for NASA's Viking Program and methods whereby it would be possible to determine at any point in time the principal organic constituents that had been delivered to a planetary body, specifically Mars.

The group agreed that the most significant obstacles to some of the biological experiments would probably be retroexhaust gases (primarily hydrazine) and reaction water. The group was also made aware of NASA's policy for Viking (Mars) in regard to the soil samples used for organic analysis studies, i.e., that samples should contain less than one part in 10 million of organic material released from the space vehicle. This design criterion was considered acceptably conservative. It was noted that a mathematical model developed by Exotech, Inc., showed that within a 10-kilometer, 1-sigma dispersion radius, this standard could be attained in a cylindrical soil sample 10 centimeters deep, with a 2.5×10^4 kilogram organic constituent burden on the space vehicle.

The essential problem in life detection experiments on the planet would be the question of whether the evidence obtained resulted from contamination delivered by a space vehicle or reflected processes indigenous to the planet. In view of this difficulty, it would be necessary to know which organic constituents had been delivered, when they were deposited, and the exact area of space vehicle impact. Thus, the group recommended the following:

1. The storage of piece-part specifications of spacecraft destined for planetary objectives. Computer storage is envisioned as a desirable method to allow rapid retrieval.
2. The storage of a reasonably sized sample of any organic compound where more than 25 kilograms of that compound are used in any single planetary-bound mission. Sealed storage in an inert gas is envisioned as a desirable method to preserve the organic sample.
3. The length of storage be designed for a range of 15 to 20 years.
4. The appropriate measures be taken to determine from other launching nations their methods of organic constituents inventory and to make preliminary arrangements for the exchange of such data, should the need arise.

U.S. POLICY

In reviewing U.S. policy toward planetary quarantine, Steg and Cornell emphasize that it should be done "in terms of the work and parameter evaluations which instigated this policy through the COSPAR agreements" (Steg and Cornell, 1969, p. 514). They believe that it is particularly important to reassess the value given to the parameter v by Sagan and Coleman. This parameter refers to the probability (10^{-3}) that one

viable micro-organism is aboard a landing capsule at the time it lands on the Martian surface. The authors believe that, "Apparently no previous attempt has been made to develop a model involving v which also takes cognizance of the type of biological risks foreseeable and which formulates conceptions of these risks in relative numerical terms." (Steg and Cornell, 1969, p. 514).

. . . which includes both expected losses from failures to collect data and from contamination to analyze the quarantine problem, (and) evidence is given which suggests that the current quarantine requirements may be too strict if their implementation forces a program delay. (They feel that) U.S. policy should be reexamined, keeping more fully in mind both the types and the relative sizes of the losses which might be encountered.

Mission Loss Steg and Cornell conservatively assume that any significant contamination resulting from one mission will spread rapidly enough to adversely affect the following mission. That is, they are concerned with an information loss $f(k)$ on mission k resulting from some experimental failure, and a contaminating loss $g(k)$. Table 10 shows mission loss where the authors assume that all evidence collected from Mars will be biased after the planet is contaminated.

Table 10 *Mission Loss (after Steg and Cornell, 1969, p. 515).*

	Unbiased Data	Biased or No Data
No significant contamination	0^1	$f(k)^2$
Significant contamination	$g(k)^3$	$f(k)+g(k)^1$

They index the outcomes of the missions by the integers in the upper right area of the cells, and assume that there is a constant probability for these outcomes over missions. The probability of that respective outcome is written as p_i, with $i = 1, 2, 3$, or 4, the cell index.

The parameter (p_i) values for a single mission are calculated from the following, where C = significant contamination; $\bar{C}$ = no significant contamination; D = unbiased data; $\bar{D}$ = biased or no data:

$$p_1 = P(\bar{C}, D) = P(D|\bar{C}) \cdot P(\bar{C}) \doteq P(D) \cdot P(\bar{C}) = P(D) \cdot (1 - P(C))$$

when $P(C)$ is small,

since $P(D) = P(D|C) \cdot P(C) + P(D|\bar{C}) \cdot P(\bar{C}) \doteq P(D|\bar{C})$ when $P(C)$ is small.

$$p_2 = P(C, \bar{D}) \doteq (1 - P(D)) \cdot P(\bar{C}) = (1 - P(D)) \cdot (1 - P(C))$$

$$p_3 = P(C, D) = P(D|C) \cdot P(C)$$

$$p_4 = P(C, \bar{D}) = (1 - P(D|C)) \cdot P(C)$$

where

$P(C)$ P (viable organism aboard) P (release|aboard) P (C|release, aboard), P (release|aboard) $= P$(soft land) $\cdot$ P(release|soft land, aboard) $+ p$ (crash land) $\cdot$ P (release|crash, aboard).

$P(D)$ P (D|soft land) $\cdot$ P (soft land)

$P(D|C)$ $P(D|C$, soft land) $\cdot$ P (soft land)

Wherever possible, Steg and Cornell use the Sagan-Coleman values to assign numerical values to these probabilities. Thus, they use the probability of significant Martian contamination following the release of a single organism as $P(C|\text{release, aboard}) = 10^{-2}$, but with the assumption that the contamination, if present, will spread rapidly between missions. They also use the Sagan-Coleman release probability P (release|aboard) = 1 and P(crash) = 0.1 (when P (soft land) = 0.9). $P(D|\text{soft land})$ is accepted as 0.9 to show a good chance of successfully collecting data following a soft landing, and P ($D|C$, soft land) $= 10^{-2}$ to indicate the probable biased nature of data acquired on a contaminating mission. In addition, $v = P$ (viable organism aboard), so that the result is $p_1 = 0.81\ (1 - v \cdot 10^{-2})$, $p_2 = 0.19(1 - v \cdot 10^{-2})$, $p_3 = 0.009 \cdot v \cdot 10^{-2}$, and $p_4 = 0.991 \cdot v \cdot 10^{-2}$.

In selecting informational loss functions, Steg and Cornell use three different forms:

$$f_1(k) = a \cdot k$$

$$f_2(k) = b$$

$$f_3(k) = c|k^{-}$$

where a, b, and c are constants selected so that $\Sigma_{k=1}^{N} f_j(k) = 100$, $j = 1$, 2, and 3. When $N = 30$, then $a = 0.21505376$, $b = 3.33333333$, and $c = 25.0313696$ (Steg and Cornell, 1969, p. 516).

These $f(k)$ functions represent different possible forms of sequential data loss and are increasing, constant, and decreasing, or alternatively, their cumulatives are respectively concave, linear, and convex in k. (They) stress that the numerical values assigned the $f(k)$ functions are dimensionless, with the choice of $\Sigma_{k=1}^{N} f_j(k) = 100$ arbitrary and indicating only its value relative to the contamination loss $g(k)$. It is solely the relative size of the two losses which is of importance, and without considering their comparative size meaningful losses could not be assigned.

Risk Values Steg and Cornell tentatively adopt a constant $g(k)$ function with a size of 100; therefore, the loss resulting from contaminating

Mars is independent of the particular mission in which it occurred. The authors can then arrive at a total risk by combining each of the possible losses by weighting them with the probability that it is incurred and summing over all such losses. Table 11 shows the values for the risk, with $v = P$ (viable organism aboard) ranging from 1 to 10^{-6} and for delays of 0, 1, 3, and 6 missions. A delay is defined as "the number of missions that the start of the program must be postponed to achieve satisfactory reliability of all spacecraft components under sterilization methods required to obtain probability level v" (Steg and Cornell, 1969, p. 516). Two of the values, $v = 1$ under f_2 and $v = 10^{-1}$ for a one-mission delay, suggest that the lander program should be unconditionally delayed. That is, there is too great a chance of contaminating the planet with the large v probability relative to the value of the information which might be obtained when f_1 indicates that value.

Table 11 *Values for Risk (after Steg and Cornell, 1969, p. 516).*

v	f_1	f_2	f_3	f_1	f_2	f_3
	No Delay			One-Mission Delay		
1	59.819	56.444	50.689	58.577	57.694	69.459
10^{-1}	23.585	23.199	22.560	23.583	25.723	42.658
10^{-2}	19.464	19.425	19.360	19.620	22.107	39.618
10^{-3}	19.046	19.043	19.036	19.219	21.741	39.310
10^{-4}	19.005	19.004	19.004	19.179	21.704	39.279
10^{-5}	19.000	19.000	19.000	19.175	21.700	39.276
10^{-6}	19.000	19.000	19.000	19.174	21.700	39.275
	Three-Mission Delay			Six-Mission Delay		
1	56.581	60.233	83.809	54.827	64.138	92.901
10^{-1}	24.101	30.776	59.249	26.187	38.376	71.344
10^{-2}	20.455	27.472	56.483	23.014	35.521	68.944
10^{-3}	20.086	27.137	56.203	22.694	35.232	68.702
10^{-4}	20.049	27.104	56.175	22.661	35.203	68.677
10^{-5}	20.046	27.100	56.172	22.658	35.200	68.675
10^{-6}	20.045	27.100	56.172	22.658	35.200	68.675

As an example, Steg and Cornell compare the $v = 10^{-1}$ value for no delay value with the $v = 10^{-2}$ three-mission delay value. If the design of a spacecraft is improved so that it has a lower level of contamination without its reliability being affected, then the delay with its lower risk should be accepted. "Six 'no-delay' entries admit smaller 'delay' risks of the next lower order of v, but the 'no-delay' risks are smallest for $v \leq$

10^{-3} under f_1, $v \leq 10^{-2}$ under f_2, and $v \leq 10^{-1}$ under f_3" (Steg and Cornell, 1969, p. 517).

The authors have also determined the risks in using the (Steg and Cornell, 1969, p. 517)

> . . . constant loss $g(k) = 1000$, and the variable loss, depending on the contaminating mission B, which varies from 200 down to 100 with increasing B, making it more costly for a more prolonged period of contamination prior to manned landings. In the second case the results were like those already cited, but in the first case the "no-delay" risks were smallest only for v values of around one order of magnitude smaller. However, assuming 18 total lander missions on the basis of an average of three missions at each opportunity between 1973 and 1984, the risks indicated, under the three forms of f and of g previously considered, calling for a delay if the best achievable level is $v > 10^{-1}$, but none if $v \leq 10^{-2}$. Values between 10^{-2} and 10^{-1} gave varying results depending on the forms of the losses assumed.

An alternative for viewing these results is to determine what constant g value would lead to identical risks for not delaying at the $v = 10^m$ level and for delaying one mission to attain a $v^* = 10^{m-1}$ value. In Table 12, the authors provide the g values for each of the three f loss functions. (Steg and Cornell, 1969, pp. 517–518).

Table 12 *Constant g Losses Yielding Equal Risks Where the v* Level Requires a One-Mission Delay (after Steg and Cornell, 1969, p. 518).*

v	v^*	f_1	f_2	f_3
1	10^{-1}	−56.392	−32.591	65.338
10^{-1}	10^{-2}	−48.652	59.037	739.511
10^{-2}	10^{-3}	9.392	955.908	7473.121
10^{-3}	10^{-4}	587.914	9922.717	74808.436
10^{-4}	10^{-5}	6372.942	99590.616	748161.516
10^{-5}	10^{-6}	64223.320	996269.582	7481692.310

Since rather large values of g are thought to be inconsistent with the importance of obtaining data on Mars before manned landings, that is with $\Sigma_{k=1}^{N} fj(k) = 100$, this table indicates less risk for going forward with the lander program rather than delaying it, at least for a level $v \leq 10^{-4}$ under f_1, $v \leq 10^{-3}$ under f_2, and $v \leq 10^{-2}$ under f_3. If a two- or more-mission delay were required to attain v, these values can be made an order of magnitude larger or more.

Steg and Cornell regard their results as conservative because the probability of the release of organisms and the resulting significant contamination of the planet are likely to be much less than that which they have assumed. Using an increasing f_1 function, they agree with the value v (1.86×10^{-3}), when $N = 30$, in the Sagan-Coleman model, even with a one-mission delay. However, when there is a greater than three-mission delay, an f_1 loss function suggests a quarantine level of $v = 10^{-2}$ (Steg and Cornell, 1969, p. 518).

Under a constant f_2 or decreasing f_3 function a value of $v=10^{-2}$ should suffice, in fact of $v=10^{-1}$ in the latter case. A decreasing loss would seem most appropriate, since this corresponds to assigning larger losses to the failure to gain data early in the program than during later missions. Such a loss would require truncation of the last, more complex missions due to a lack of preliminary Martian data acquisition. Under this form of loss as given by f_3, the current international level of $v=10^{-3}$ (Horowitz et al., 1967), as well as the modified Sagan-Coleman value, assigns little weight to f relative to g. It would seem reasonable to weight these losses more equally. United States policy should be re-examined, it appears, with interest focused on the forms and relative sizes of data collection failure and contamination losses.

COSPAR PLANETARY CONTAMINATION PROBABILITY

In preparation for the 1970 COSPAR meeting in Leningrad, Exotech, Inc., provided some supporting material for NASA regarding the *Re-evaluation of Planetary Quarantine Constraints.* Material from the December 11, 1969, discussions of the SSB at Stanford University was also included. In regard to Mars missions, it was noted that there has been increasing interest in the desirability of computing a cumulative probability for planetary contamination and in the maintenance of a contamination log. It was recommended that a clear distinction be made between the evaluation of data from past missions and the establishment of requirements for future missions in terms of two parameters generally set by COSPAR: (1) the probability that Mars will be contaminated during the quarantine period (P_C) and (2) the estimated number of missions during that period.

One issue raised in this report is (Exotech, Inc., *Re-evaluation of Planetary Quarantine Constraints*, 1970, pp. 1–2)

> . . . whether the risk of planetary contamination inherent in past flight, as estimated by the cumulative value of P_C in the contamination log, should not also influence the value of P_C used to set requirements for future flights. The difficulty of such an approach derives from the considerable discrepancy between the precautions taken (and reported) by the U.S. and U.S.S.R. in implementing past flights. The untenable conclusion which might result is that precautionary measures by the U.S. would have to be increased because the U.S.S.R. has not in the past taken these constraints very seriously. It is therefore rather pointless to subtract from $P_C=10^{-3}$ the cumulative value of planetary contamination to date in order to arrive at a value of P_C for the future.

An analysis of the data contained in the contamination log reveals that postflight contamination estimates are consistent with a risk level considered acceptable when the quarantine standard is taken seriously. However, it is felt that when the constraint is not viewed seriously, there is no way of evaluating the probability that the flight contaminated the planet. On this basis, the report suggests that the value of P_C equal to 10^{-3} be retained and used only for future missions.

The application of the planetary contamination probability to the estimated number of missions is also reevaluated. In order to keep past

and future flights separate, the reassessment of the number of missions for the quarantine period (1970–1988) is recommended. A total of 90 missions by all nations is considered a conservative value for this period, but is an appropriate number for the 10^{-3} contamination probability.

In terms of the outer planet missions being planned by NASA, it is thought that quarantine standards should be established in a different manner than were those for the Mars missions. This position is based on the following considerations:

1. It would be very difficult to obtain any kind of meaningful estimate of the number of such missions that might take place in the future, or of the period of biological exploration to be used in such an estimate.
2. There is no knowledge at the moment that can provide a basis for estimating the probability of microbial growth on the outer planets.

The report purposes that the constraints for missions to the outer planets be based on past experience with flyby missions to other planets, by formulating the standard in terms of the probability that one or more viable terrestrial organisms will be deposited on the planet as a result of the flight. One or more is defined as the risk level considered acceptable for the mission, without having to estimate the total number of missions to the planet, the acceptable probability of contamination over the entire program of such flights, or the probability of microbial growth on the outer planets. Two categories of precautions are considered: the accidental impact of the entire spacecraft or a large part of it and ejecta sources. The constraint is stated in the form of a probability of microbial arrival on the outer planet, and a value on the order of 10^{-3} or 10^{-4} is considered likely, although further analysis would be needed before arriving at a final standard.

The 13th Plenary Meeting of COSPAR and the 11th International Space Science Symposium met in Leningrad May 20–29, 1970. The report of the Panel on Planetary Quarantine expressed concern over the U.S.S.R.'s failure to submit contamination reports on their probes in compliance with COSPAR Resolution 26.5 and other recommendations. It was felt that the absence of such information, particularly concerning future missions, jeopardized the efforts of the panel.

The panel also suggested that research be initiated on possible aerosol propagation of organisms in simulated Venus environments and on the growth of organisms in clouds and on other planets, in terms of such questions as the possibility of floating populations (on Venus and Jupiter). Some of the problems of possible contamination of solar system objects other than Mars and Venus (e.g., Jupiter and its satellites) were also considered.

The panel recommended that, for the present, the same quarantine constraints used for Mars be applied to the Jovian planets, but that the multiplication of micro-organisms in simulated Jovian atmospheres continue to be studied. The panel considered the importance of extra-terrestrial bodies subjected to quarantine requirements in the following order: Mars, Venus, and Jupiter first, then Saturn, Uranus, Neptune, the Galilean satellites of Jupiter, Titan, Triton, and the comets.

The COSPAR planetary contamination model was also the subject of come criticism by the panel, in that the model did not assign errors of estimation to the terms of the equation. However, because it is a useful approximation, the model has provided the quarantine problem with a sound quantitative basis (Hedén, 1970, p. 66).

By establishing an arbitrary value representing the overall probability of contaminating a particular planet and equating this to a simple function which takes into account the various sources of contamination, it has become feasible to quantify and to reduce the principal contamination hazards on a systems basis. It is not trivial, however, to examine the consequences of using a model devoid of error terms and to protest the continued dependence on an equation which is mathematically incomplete.

To improve the model, the panel prepared a working paper showing how the current equation might be misleading and proposing the inclusion of error terms to bring it up to date.

The "Memorandum on Estimating Probability Parameters" (Hedén, 1970, p. 71) notes that an overall standard represents a number of individual properties that are estimates and, therefore, subject to error. In the past, this has not been sufficiently taken into account. Until now, the most adverse probability has been used for individual terms, and, thus, the overall probabilities have erred on the conservative side. The uncertainties of these individual parameters should be considered to produce more realistic overall probabilities. The basic assumption used in this analysis is that the uncertainties of estimates are Gaussian normal on a logarithmic scale.

Probability Parameters Consider the following parameters with mnemonic subscripts, $P(f_i')$ probability of impact of a flyby i, n_i a small number of viable organisms released at impact, and $P(g)$ the probability of a micro-organism's being able to grow. The probability of a planet's being contaminated, $P(C_i)$, is simplified as $P(C_i) = P(f_i') \times n_i \times P(g)$.

The estimates of these parameters are

Parameter	Value	Logarithm
$P(f_i')$	0.001	-3
n_i	10.0	1
$P(g)$	0.01	-2

This gives a $P(C_i)$ of 0.000, 1; $\log P(C_i) = -4$.

The term n_i is assumed to be small enough relative to $P(f_i')$ and $P(g)$ to prevent nominal probabilities over 1.0 from appearing.

Estimates of the uncertainties of the parameters take the form of standard deviations, s_f, s_n, s_g, and s_c on a logarithmic scale, but shown as positive numbers. Because flight paths can be accurately calculated, the uncertainty in $P(f_i')$ is generally small. If s_f is taken to be 0.05, it is approximately equivalent to an estimate of $P(f_i')$ as $0.001 \pm 0.00{,}11$. With additional data, the estimate of n_i may be fairly precise (half a log unit), so that $s_n = 0.5$.

Since the estimate of $P(g)$ depends on a consensus regarding the chance of growth in an unknown habitat by any one of many species, it does not provide a clear-cut answer. If $P(g)$ is estimated to be 0.01, it still contains a great deal of uncertainty because of the differences in opinion concerning the planetary conditions, organisms, and other factors. If this was meant to be an upper limit, then a more likely value of $P(g)$ might be only 0.001, but it would not be considered as high as 0.1 or as low as 0.000,01 (Space Science Board, 1970, p. 72).

If the term "unlikely" means that we are prepared to say that we may be wrong in only a few percent of cases, we could relate this to the normal distribution. Thus, 2.3% of errors on the two extremes corresponds to two standard deviations. We might therefore amend $P(g)$ to have an expected (Mean) value of 0.001, with 2 S.D. upper and lower limits of 0.1 and 0.000,1 (i.e. two powers of ten each way) giving s_g equal to 1 power of 10, = 1.0.

If the parameters are amended, then the following results would be obtained in logarithms:

Parameter	Expected	s	$2s$
$P(f_i')$	-3	0.05	0.10
n_i'	1	0.5	1.0
$P(g)$	-3	1.0	2.0

By approaching parameters in this way, attention is drawn to the most uncertain ones and how to estimate them. Provided the standard deviations are independent, the overall uncertainty of combined probabilities can be shown by adding the variances. Thus, "log $P(C_i)$ has an expected (mean) value of -5.0, while s_c is obtained as the square root of $s_f^2 + s_n^2$, which here comes to root (1.2525) = 1.192" (Sneath, 1970, p. 73).

Two S.D. limits on log $P(C_i)$ are $(-5+2.384)$ and $(-5-2.384)$. This provides upper, expected, and lower limits as shown.

Limit	$\log P(C_i)$	$P(C_i)$
Upper 2 S.D.	-2.616	0.0024
Expected	-5.0	0.000,01
Lower 2 S.D.	-7.384	0.000,000,041

Comparing this with the P_C estimated value (0.0001) above, it can be seen that by taking into consideration the uncertainties of the parameters, the value could be as high as 0.0024 at the two S.D. confidence level, despite the fact that $P(g)$ was assumed to be higher (0.01).

It should be pointed out, however, that this example is not applicable to parameters with a probability close to 1 or to those that produce nominal probabilities close to or higher than 1, as with great numbers of viable organisms.

Release of Viable Organisms The SSB submitted a report to COSPAR at the 1970 meeting concerning various aspects of the U.S. space science program. In regard to sterilization and quarantine, it was observed that the probability of growth (P_g) of viable terrestrial organisms (VTO's) on Mars was studied further within the context of the data obtained from *Mariner 6* and *Mariner 7*. The SSB concluded that there is no justification for changing P_g from the value of 1×10^{-3}. The problem of the release of viable organisms from the interior of a solid was also analyzed in terms of evidence supplied by The Boeing Corporation. Boeing had fired plastic pellets impregnated with viable spores at varying speeds against sterile targets and found that survival of the organisms varied inversely with the velocity of impact. They believe that the overall release probability (Pr) of VTO's from a spacecraft's interior cannot be set at less than 1×10^{-3}, and that encapsulated organisms must be killed prior to launch in order to reduce the Pr value.

An ad hoc Review Group on the Review of Sterilization Parameter Probability of Growth (P_G) met at Woods Hole, Massachusetts, July 16–17, 1970, to review and discuss the parameter P_g and its role in the sterilization allocation model. Certain points or guidelines were developed as a basis for reevaluating the parameter for the probability of growth (Porter, 1970, p. 1).

> The probability estimate of P_g begins with the assumption that at least one viable terrestrial organism has been released to the planetary surface by any means; e.g., as a result of a crash landing or through eolian erosion. In accordance with the above definition, the parameter for probability of release has not been directly considered in this evaluation nor is it implicitly contained in the estimate of P_g.

Any attempt to quantitatively estimate the absolute value of the growth (contamination) probability was regarded as unrealistic. It was thought that the reevaluation of P_g should be centered on the uncertainties in the estimates of each subparameter contributing to P_g which, together, could lead to the proliferation of infected microenvironments. On the basis of these points, the group adopted this procedure for the reevaluation of P_g.

1. Establish the minimum conditions that are necessary to define a

microenvironment (ME) which would support growth of the most hardy terrestrial organisms (HTO's).

2. Estimate the probability (P_{me}) that such ME's exist on the surface of Mars.
3. Estimate the probability (P_{hto}) that an HTO capable of growing in the defined ME exists among the organisms present in and on spacecraft.
4. Estimate the probability (P_t) that such an HTO will be transported upon release to a ME and survive the trip.

Many factors considered in previous P_g estimates are implicitly contained within these parameters.

Conditions for a ME minimally suitable for growth of an HTO were agreed upon, and the group outlined a two-phase effort in estimating the probabilities P_{me}, P_{hto}, and P_t : (1) estimate the probability numbers on the basis of a 50–50 chance of their likelihood (even betting odds) and (2) reconsider the probability estimates on the basis of a 0.999 confidence factor upper limit estimate; i.e., one-thousand-to-one betting odds that the probability, if it could be determined, would not be greater than the value given. The numbers listed below (Table 13) are averages of estimates given by individual members of the review group.

Table 13 *Estimates for Growth of an HTO (after Porter, 1970).*

	Even-Odds Estimate	0.999 Confidence Factor–Upper Limit Estimate
$P_{me} \leqslant$	1×10^{-2}	1
$P_{hto} \leqslant$	3×10^{-4}	1×10^{-2}
$P_t \leqslant$	1×10^{-3}	1×10^{-2}
$P_g \leqslant P_{me} \cdot P_{hto} \cdot P_t$	3×10^{-9}	1×10^{-4}

There is a significant increase in the probability of growth with the requirements for a high level of confidence in each of the estimates. This result appears to be a function of the lack of evidence concerning conditions on the Martian surface and, therefore, the review group recommended that until more information about Mars is obtained, NASA should use the value of $P_g = 1 \times 10^{-4}$ for its spacecraft sterilization allocation model. It was also pointed out that this is a conservative value, and excess safety margins in carrying out the quarantine requirements should be avoided.

New Contamination Allocations It was suggested at the 1970 COSPAR meeting that an estimate of 50 missions is more reasonable for flights to Mars through 1988 than the 100 unmanned flights previously considered.

In conjunction with the procedure to recover unused parts of the contamination allocations of completed flights, these factors affect the contamination probability of individual missions. Consequently, in a report to NASA, Exotech, Inc., proposed new contamination allocations for future Mars flights within the context of these developments. The conclusions of the report are summarized in Table 14.

Table 14 *New Contamination Allocations for Future Mars Flights (after Exotech, Inc., TRSR 70-42, 1970, p. 8).*

	Previous	New
Requirement: Probability that mission will contaminate Mars for		
a. Orbiter or flyby (e.g., 1971)	3×10^{-5}	7.1×10^{-5}
b. Orbiter/lander mission (e.g., 1975)	3.14×10^{-5}	7.2×10^{-5}
c. Direct lander mission	—	1×10^{-6}
Basis—COSPAR Recommendations		
a. Probability that Mars will be contaminated before 1989	10^{-3}	10^{-3} with credit for past missions
b. Estimated number of missions during unmanned exploration	100	50

The new values required estimates based on the probability of contamination by past flights, as well as the number and type of future flights. The report estimated that there would be 18 U.S. Mars missions between 1970 and 1988, making a total of 22 since 1964. For the 22 missions, a value of 4.4×10^{-4} was derived from a uniform allocation of the total probability of planetary contamination (1×10^{-3}). A total allocation of about 4.4×10^{-4} was obtained for the 18 future missions by subtracting 2×10^{-7} (the allocation already used) from the U.S. allocation of 4.4×10^{-4}.

This value was then suballocated to individual missions through the use of the following formula:

$$P_c = NP(N) + N'P(N') \tag{1}$$

where

P_c	the total probability of contamination
N	the number of lander vehicles
$P(N)$	the probability of contamination by each lander vehicle
N'	the number of nonlander vehicles
$P(N')$	the probability of contamination by each nonlander vehicle

Equation (1) was then applied to future U.S. Mars flights by estimating values for N and N' based on the assumptions that there will be two or

more orbiter missions and four more orbiter/lander missions and that the 12 remaining missions will be direct landers. Thus, there would be 16 lander vehicles (N) and six orbiting vehicles (N'). Equation (1) would then become $4.4 \times 10^{-4} = 16\,P(N) + 6\,P(N')$. Considering the range of values of $P(N)$ and $P(N')$ that satisfy the equation, a point allotting about 97 percent of the total U.S. unused contamination allocation to the six orbiters and the remainder to the landers was selected as a feasible choice. This, in turn, produced allocations of contamination probabilities for future orbiters and landers as follows: orbiter mission $= 7.1 \times 10^{-5}$, and lander missions $= 1 \times 10^{-6}$. The sum of these values would be allocated to a combined orbiter/lander mission.

Nonlander Contamination Probabilities A report, *Estimation of Planetary Contamination Probabilities by Non-Landing Vehicles*, was prepared by Exotech, Inc., in 1970. The intent was to clarify the procedures used to estimate the probabilities of potential sources of planetary contamination from nonlanding vehicles and to identify their analytical basis.

$P(N')$ is designated as the overall constraint for the probability that a nonlander (flyby or orbiter) will accidentally contaminate a planet. Since it is far less than unity and since one source of contamination (P_i) is assumed to independently result in planetary contamination,

$$P(N') = \sum^{i} P_i \tag{1}$$

The probability P_i is conditional on the probability of source arrival, $P(A)$, i.e., the contamination source must reach the planet:

$$P_i = P(A) \cdot P(C|A) \tag{2}$$

On the assumption that the source does arrive, $P(C\,|\,A)$ is the probability that it will contaminate the planet. $P(A)$ and $P(C\,|\,A)$ differ in that the former refers to the contamination source as a whole, while the latter deals with contamination in regard to the organisms carried by the source.

In order to establish an appropriate relationship for $P(C\,|\,A)$, the report defines the following terms:

- n — the number of viable micro-organisms contained in the source before considering any events which will produce or deter contamination
- $P(n)$ — the probability that any one of the n micro-organisms in the source will contaminate the planet

The contamination process is assumed to follow a binomial distribution which, according to the report, implies the following:

1. Contamination by one organism in the source is independent of the other organisms in the source.
2. n represents the number of repeated "trials" to contaminate the planet.
3. $P(n)$ represents the probability of contamination in any one "trial."

These, in turn, lead to

$$P(C|A)=1-[1-P(n)]^n \tag{3}$$

On the basis of equation (2), the following relationship is given:

$$P_i=P(A)\{1-[1-P(n)]^n\} \tag{4}$$

The series expansion of equation (3) is examined, as well as the pertinent approximations, to facilitate estimation. Since $[P(n)]^2 \ll 1$, the following expansion can be used:

$$P(C|A)=n\cdot P(n)-\frac{n(n-1)}{2!}[P(n)]^2+\frac{n(n-1)(n-2)}{3!}[P(n)]^3-\ldots \tag{5}$$

When the population of organisms is assumed to be very large and $P(n) \ll 1$, a useful approximation can be obtained. If

$$n\cdot P(n) \geqslant 1 \tag{6}$$

and since $n \gg 1$, with reference to the series expansion of equation (5), then $n-1 \approx n$; $n-2 \approx n$; $n-3 \approx n$, etc.

For condition $n\cdot P(n) \geqslant 1$ in equation (6),

$$P(C|A) \geqslant 1-1/2!+1/3!+1/4!+\ldots \text{ or } P(C|A) \geqslant 0.63.$$

Therefore,

$$1 > P(C|A) \geqslant 0.63 \tag{7}$$

The $P(C|A)$ range does not differ greatly from unity and can be assumed to be great enough to make $P(C|A) \approx 1$. Thus, the P_i estimate reduces to

$$P_i=P(A), \text{ for } n\cdot P(n) \geqslant 1 \tag{8}$$

When condition (6) cannot be assumed, then, generally, $n > 10$, and the series expansion of (5) becomes

$$P(C|A) = n \cdot P(n) - \frac{1}{2!}[n \cdot P(n)]^2 + \frac{1}{3!}[n \cdot P(n)]^3 - \ldots \quad (9)$$

But since the case is for $n \cdot P(n) \ll 1$, which makes all of the terms in equation (9) successively smaller, then $P(C|A) \approx n \cdot P(n)$ and

$$P_i = P(A) \cdot n \cdot P(n), \text{for } n \cdot P(n) \ll 1 \quad (10)$$

$P(A)$ and $P(n)$ represent the probabilities of subevents which must take place in order for $P(A)$ and $P(n)$ to occur. The result is

$$P(A) = P_1(A) \cdot P_2(A) \cdot P_3(A) \ldots \quad (11)$$

$$P(n) = P_1(n) \cdot P_2(n) \cdot P_3(n) \ldots \quad (12)$$

$P_1(A)$ and $P_k(n)$ are the individual subevents.

The number of micro-organisms within the source is designated as n. Since not all of the organisms that are potentially in the source will contribute to it,

$$n = n(o) \cdot P_{nT} \quad (13)$$

where

$n(o)$ the potential source population

P_{nT} the probability that any one organism of the potential population will be transferred into the source

The mean source population is thus defined by n.

The report summarizes these relationships in the following two equations:

(1) If $n \cdot P(n) \geq 1$

$$P_i = P(A) \quad (14)$$

(2) If $n \cdot P(n) \ll 1$

$$P_i = \prod^{j} P_j(A) \cdot n(o) \cdot P(nT) \cdot \prod^{k} P_k(n) \quad (15)$$

The contamination sources are then classified as a large microbial

source (or large impactable source), P_L, whose estimation refers to the evaluation of accidental impact of the source on the planet. This is further divided into (1) small microbial sources (P_s), where the organisms are embedded in the source material, and (2) free sources (P_F), i.e., individual free organisms.

The relationships used for the three categories are:

Large microbial sources:

$$P_L = P_{CR} \cdot P_I \tag{16}$$

Small microbial sources:

$$P_S = P_{CR} \cdot P_I \cdot P_{SE} \cdot P_{ST} \cdot P_{SA} \cdot P_R \cdot P_G \cdot n(o) \cdot P_{nT} \tag{17}$$

Free microbial sources:

$$P_F = P_{CR} \cdot P_I \cdot P_{SE} \cdot P_{ST} \cdot P_{SA} \cdot P_G \cdot n(o) \cdot P_nT \tag{18}$$

The symbols for the subevents are designated by the following questions:

P_{CR}	Is source created?
P_I	Does source impact planet?
P_{SE}	Does it survive source creation (ejection) process?
P_{ST}	Does it survive transport to planet?
P_{SA}	Does it survive entry through planet's atmosphere?
P_R	Is it released onto planet's surface?
P_G	Does it grow, spread, and lead to microbial proliferation on the planet?
$n(o)$	What is potential population?
P_{nT}	Will any one of potential population become a member of the source?

The report concludes with a suggested sequence to be followed for estimating the probability of planetary contamination by nonlanders, where a particular source has an allocation of P_i:

1. Estimate the probability of arrival $P(A)$. If it is equal to or less than the allocation P_i, then no further work is needed, since the load can be assumed to be very large and the condition $n \cdot P(n) > 1$ will be met. This also implies that knowledge of the load will not be necessary.
2. If $P(A) < P_i$, a basis exists for estimating the desired values of $P(n)$ so as not to impose rigorous limits on the allowable $n(o)$.

3. Based on estimated values of $P(A)$ and $P(n)$, the degree of bioassay and/or decontamination can be established to meet the allocation P_i for the specific source. Alternately, changes in mission design can be considered, e.g., trajectory biasing, so as to reduce $P(A)$ and thereby obviate the need for bioassay and/or decontamination.

SAFETY MARGINS

Implementation of the upper bound constraint on the probability of planetary contamination involves an analysis of individual contamination sources and an estimation of individual parameters such as the mean number of organisms associated with a contamination source or the probability that they will be released onto the surface of the planet. How conservatively these parameters are estimated will affect the stringency of precautionary measures to be applied, e.g., the length of heat sterilization cycles. Conversely, the safety margin or confidence level in the attainment of the upper bound probability that the source will contaminate the planet is also determined by this process. Schalkowsky and Jacoby (1973, p. 14) reported the following:

> The 1970 COSPAR meeting focused on these safety margins in the implementation of Planetary Quarantine requirements. At this meeting, it was noted that the various parameters used to determine the probability of contamination are random variables which must be estimated. As any estimation procedure has its associated errors, attention was focused on the effect of these errors on the implementation process.

Schalkowsky and Jacoby describe a number of alternatives to the implementation of the COSPAR recommendations, with particular emphasis on their utility in attaining the desired minimization of excessive safety margins and on their effect on implementation procedures. They point out that any attempt to include the effect of uncertainties in the process by which parameters are estimated invariably leads to the problem of what confidence limits are to be used with the applied constraints. Constraints on individual sources of contamination are derived through a process of administrative suballocations from the overall constraint ($P_c \leq 10^{-3}$) that a planet will be contaminated during the period of biological exploration. Thus, the confidence value associated with the constraint on the individual source of contamination would be related to the overall constraint. Within this context, it would appear that the desire of the COSPAR Panel on Planetary Quarantine to "defend the assumption that the overall chance of planetary contamination is in fact the value assigned" would make it necessary to

designate a confidence value, as well as the upper bound constraint. Schalkowsky and Jacoby do not consider this a practical undertaking in terms of either the credibility of the resultant constraints or their implementation.

The selection of $P_c \leq 10^{-3}$ as an overall constraint is necessarily (Schalkowsky and Jacoby, 1973, p. 21)

> . . . quite arbitrary, and any value for P_c less than unity would achieve the basic objective of leading to a systematic evaluation of all potential sources of planetary contamination. To superimpose on this arbitrary upper bound constraint another arbitrary confidence constraint would certainly not make the combined constraints any more credible. For, if the objective was to change the desired risk level, this could simply be done by modifying the value of P_c itself.

The authors believe that the only justification for considering such an additional confidence constraint would be based on an effort to facilitate the implementation process. However, this is regarded as an unlikely possibility.

The difficulty in estimating individual parameters is illustrated by the interpretation of the COSPAR probability constraint to represent an expected value that would require all parameters to be estimated at their mean (or median) values. Although this would be acceptable in an analytic sense, it would not be acceptable from a practical viewpoint. For example, when (Schalkowsky and Jacoby, 1973, p. 21)

> . . . experts are asked to make a subjective estimate of a single probability value, the uncertainties invariably lead them to conservative estimates. The best that can be accomplished under these circumstances is to seek a range of estimates, bounded by conservative and median values . . . .

One of the most significant aspects of the estimation process is the relative uncertainty in the different parameters as shown by the spread between the median and upper bound values. This is particularly evident in the uncertainty in estimating the probability of microbial growth and proliferation on the planet, P_G, which significantly exceeds the uncertainty in all other parameters. Such considerations have led R. W. Porter to develop a method for increasing the degree of control to account for the uncertainties in estimation. His analysis requires the selection of a confidence constraint on the allocation and some estimate of the range of uncertainties in all the parameters in order to permit the computation of the differential degree of control, ΔC, to be attributed to the uncertainties.

The relationships described above are formalized in the following equation:

$$\Delta C = K_A \sqrt{\Sigma \sigma_i^2} \tag{1}$$

where K_A is the quantile of the normal distribution corresponding to the desired confidence c_A; e.g., for $c_A=0.99$, $K_A=2.33$. Thus, the incremental control would be based on the degree of uncertainty in all the parameters as represented by their variances (σ_i^2) and by the desired confidence in the attainment of the allocation (K_A). However, a quantitative evaluation is not possible without some further knowledge of the variances (σ_i^2) and associated standard derivations (σ_i). Since the greatest uncertainties are associated with the parameter P_G, probably equaling or exceeding the uncertainties in all other parameters of a particular contamination source, it is assumed that

$$\sigma_G=\sigma_N+\sigma_{AE}+\sigma_{CE}+\sigma_C \tag{2}$$

and

$$\sigma_N \approx \sigma_{AE} \approx \sigma_{CE} \approx \sigma_C \tag{3}$$

then,

$$\Delta C=K_A\sqrt{\Sigma\,\sigma_i^2}=K_A\sqrt{\sigma_G^2+4\left(\frac{\sigma_G}{4}\right)^2}=1.12\sigma_G K_A \tag{4}$$

or

$$\Delta C \approx \sigma_G K_A$$

Equation (4) is, for all practical purposes, the basis of the approach taken by the SSB at Woods Hole in recommending the use of the conservative (0.999 confidence) value of P_G, which would automatically achieve the desired increment in control. However, as Schalkowsky and Jacoby indicate, the difficulty with this approach is the associated suggestion that this conservatism not be duplicated in the estimation of the other parameters.

These considerations have led to the formulation of confidence limits on individual parameters (K_i) which are related to the desired confidence in the allocation K_A. Schalkowsky and Jacoby use the assumptions of equations (2) and (3) in equation (5):

$$K_i=K_A\frac{\sqrt{\Sigma\sigma^2}_i}{\Sigma\sigma_i}=\frac{\sqrt{\sigma_N^2+\sigma_{CE}^2+\sigma_{AE}^2+\sigma_G^2+\sigma_C^2}}{\sigma_N+\sigma_{CE}+\sigma_{AE}+\sigma_G+\sigma_C} \tag{5}$$

They are thus able to obtain a relationship between the confidence

constraint in the estimates of individual parameters and the desired confidence in meeting the allocation constraint, as a function of the uncertainty level in the process of estimating parameters. Then,

$$K_i = K_A \frac{1.12\sigma_G}{2\sigma_G} \approx 0.5K_A \tag{6}$$

Using equation (6) as a basis, they are able to show the relationship between the confidence limits c_A and c_i.

Confidence Limit on Allocation $-c_A$	Corresponding Confidence Limit on Individual Parameters $-c_i$
0.999	0.95
0.99	0.88
0.95	0.80
0.90	0.74
0.84	0.70

Schalkowsky and Jacoby suggest that "planetary quarantine analysis continue to be based on the upper bound constraints currently in use, as derived from the basic COSPAR recommendation that $P_c \leq 10^{-3}$," and that "the addition of confidence limits at this level would not be useful and should therefore be avoided" (Schalkowsky and Jacoby, 1973, p. 23). In addition, they believe that "safety margins should be treated at the level of individual parameter estimation, i.e., in arriving at values for the biological populations, attenuating events, conditional events and applied controls" (p. 23). They also distinguished between the estimation of the range of a parameter and the selection of a value within this range. The former is regarded as a technically based judgment which should be formalized in terms of the median (0.5 confidence) and conservative (0.99 confidence) values. But "the selection of a value within the above range is not a purely quantitative procedure. It can be guided by the use of a 0.85 confidence value, utilizing the relationships of the log-normal distribution" (p. 23). However, in addition to the quantitative aspects, this choice must reflect all other considerations affecting the conservatism of the estimation process.

In a recent article in *Science and Public Affairs*, Horowitz (1971) restates his skepticism concerning planetary quarantine constraints for Mars and the sterilization requirement that there be at most one surviving micro-organism per 1,000 spacecraft. He points out the excessive cost of such a program and its effect on the reliability of the spacecraft. Horowitz claims that the assumption that Mars is a suitable habitat for the growth of terrestrial micro-organisms was defensible in 1964 when the quarantine policy was adopted, but he states (Horowitz, 1971, p. 15):

It is now abundantly clear that terrestrial life could not grow in the Martian environment. In the view of many . . . the quarantine requirements are now obsolete and should be drastically revised, if not abandoned altogether. Despite the radical revisions that have been made in recent years in our knowledge of Mars, the spacecraft sterilization requirements are virtually the same today as they were in 1964. They have become a seemingly permanent monument to a Mars that never existed.

COSPAR convened its 14th Annual Plenary and 12th International Space Science Symposium in Seattle, Washington, from June 18 to July 2, 1971. The Panel on Planetary Quarantine held an open meeting on quarantine and sterilization issues for the first time. Carl Sagan emphasized the importance of knowing the biological burden of, and the quarantine procedures for [Soviet] *Mars 2* and *3*, and the Panel urged the U.S.S.R. to provide data on these probes within the agreed time period after launch. Lawrence Hall presented the following information on *Mariner 9:* the prelaunch P_C allocation was 7.1×10^{-5}, permissible bioburden at launch was 1.0×10^5, measured bioburden was 3.1×10^4, and, thus, the postlaunch estimate of P_C was 3.4×10^{-5}.

Horowitz and Cameron (1972) presented a paper at the Seattle meeting describing the microbial populations and soil conditions in the ice-free valleys of South Victoria Land, Antarctica. These regions are the coldest and driest deserts on Earth and are in some ways similar to the Martian environment. The authors suggest that the valleys are essentially abiotic areas in which the small microbial populations are maintained by the fallout of cells blown from other locales. They believe that the implication is clear that there is only a negligible possibility that terrestrial micro-organisms can grow in the far more hostile environment of Mars.

Hoffman et al. (1972) describe the analysis approach and planetary quarantine model used in the Mariner Mars 1971 program, in which three major sources of possible contamination were identified: accidental impact of the spacecraft, loose particles, and the gases used for altitude control and pressurization. They conclude that (Hoffman et al., 1972, p. 21)

Mission strategy, including aiming point biasing and orbit periapsis altitude selection, was developed to satisfy the probability allocations for accidental spacecraft impact. To ensure that permissible microbial burden levels would not be exceeded, extensive cleaning and facility personnel control programs were implemented. The analysis and microbiological assay results indicate that the planetary quarantine constraints for the orbiter mission [were] satisfied.

PRESENT POLICIES FOR PLANETARY MISSIONS

NASA policy regarding planetary quarantine was reviewed during 1971, and new guidelines and revisions were considered. The recommended changes in policy bear upon Mars, Venus, Mercury, and the outer planets, subject to the response of the SSB.

The current probability of growth of terrestrial organisms for Mars proposed by the SSB is $P_G = 3 \times 10^{-9}$, with 50 percent confidence and $P_G = 10^{-4}$ with 99 percent confidence. The board advised NASA to adopt the conservative value ($P_G = 10^{-4}$), but since the standard has a large safety margin, it was suggested that it not be duplicated in the parameters. Since NASA prefers to use a uniform approach to the control of safety margins, at least for operational purposes, it will use the moderate 10^{-6} value for P_G. The new values reduce the required length of the heating cycle by one-half and alleviate concern for buried and mated surface contaminants.

The P_G value for Venus is, at the present time, 10^{-6} for its surface and 10^{-4} for its atmosphere. However, the suggested view probabilities are $P_G = 0$ (surface) and $P_G = 10^{-9}$ (atmosphere). A 1970 report by the SSB had recommended lower P_G values for Venus.

In view of the certainty that a 700 K temperature is present over the entire surface of the planet, there is no chance of growth by terrestrial organisms, and only a slight possibility that they could grow on airborne particles near cloud tops. Thus, there was substantial reason to change the values and relay the constraints. Sterilization procedures will be unnecessary, and only the clean assembly methods required for quality control and decontamination before launch will be required.

In 1970, the SSB designated a P_G of 1×10^{-6} for the Moon and Mercury in their report to NASA. However, it is generally accepted that the value for the Moon is near zero. The parameter for Mercury is also considered to approach zero, in view of the planet's very hot surface (500–550 K), possible lack of moisture, and thin atmosphere (5mb). Therefore, Mercury is no longer considered of biological interest and the previously imposed constraints will be dropped.

The present policy regarding the outer planets is characterized by conflicting recommendations for quarantine policy. The ad hoc committee convened by the SSB in 1970 to review COSPAR sterilization standards suggested a probability of 1×10^{-4} that viable terrestrial organisms will be deposited by flybys on the surface of or in the atmosphere of the outer planets. In contrast, the COSPAR Planetary Quarantine Panel maintained that the same parameters required for Mars should be used for the Jovian planets. In an attempt to formulate a common policy, NASA proposes to adopt the COSPAR constraint, which is compatible with procedures currently used to develop planetary quarantine standards for the planets and is consistent with present methods of quarantine analysis.

In the past, all U.S. planetary missions have been designed for capsule deflection trajectories as a quarantine safety measure. However, it now appears that bus deflection trajectories can be used, while still complying with planetary quarantine constraints in missions that would not otherwise be successful.

The orbital lifetime policy for Mars as suggested by COSPAR has, in the past, been that spacecraft shall not impact the planet prior to December 30, 1988 (the end of the period of biological interest). But this does not permit additional time to study the planet before it is contaminated, if life is found during the period of biological exploration. Consequently, the proposed new policy assigns a probability of 0.95 that an orbiting spacecraft will not impact Mars before December 30, 2018. This should allow sufficient time for the detection and study of any possible life forms on the planets.

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