

# MICROBIOLOGICAL CLEANLINESS OF THE MARS PATHFINDER SPACECRAFT

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## BIOGRAPHY

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## ABSTRACT

The recently launched Mars Pathfinder spacecraft, involving a lander and a rover scheduled to land on Mars in July 1997, was required to comply with the National Aeronautics and Space Administration planetary protection regulations for such space missions. The microbial cleanliness requirements drove a major, successful effort to assemble a clean spacecraft and to verify and maintain its cleanliness.

Planetary protection for Mars missions is introduced, and the approach taken by the Mars Pathfinder Project is discussed. Specific topics include ethyl alcohol wiping, dry heat microbial reduction, microbiological assays, and the Kennedy Space Center's SAHJ-2 clean room. Quantitative results for the number of aerobic spores found on the spacecraft are presented and compared to the Viking 1975 values.

**keywords:** contamination, Mars, microbiology, planetary protection, spacecraft

## INTRODUCTION

The Mars Pathfinder Project (MPF), which was launched to Mars on December 7, 1996, is required to meet certain planetary protection (PP) regulations, particularly in regard to the microbiological cleanliness of the spacecraft.

The planetary protection regulations for United States space missions are established by the National Aeronautics and Space Administration (NASA).<sup>1</sup> These regulations are consistent with the basic NASA planetary protection policy<sup>2</sup> and with an international treaty,<sup>3</sup> and have been reviewed by the Committee on Space Research (COSPAR), an international body charged with the oversight for compliance with the treaty. The purpose of planetary protection is to provide a reasonable level of assurance that the opportunity to search for life (and its precursors and fossil remnants) elsewhere in the solar system will not be lost due to contamination by earlier space missions. The requirements are especially stringent for landed missions to Mars, where the possibility of life is of scientific interest. Although the implementation of procedures for compliance by MPF was planned and partially completed before any report on microbial fossils in a Mars meteorite, the published findings<sup>4</sup> do add a sense of validation to the activity and to the NASA planetary protection program.

## BACKGROUND

### Mars Pathfinder Spacecraft

The flight system comprises the cruise stage, the aeroshell (heat shield and back shell) and the lander. In the launch configuration (Figure 1), the cruise stage interfaces with the motor, so that the stack under the payload fairing has the lander, inside the aeroshell, on top. Of the mechanisms employed in the entry braking, the parachute and the RAD rocket motors are packaged on the back shell. The air bag system is mounted on the outside of the lander. The flight system is assembled in a clean room, from the lander, heat shield, and back shell subsystems. After this assembly is completed, all of the lander surfaces and the interior surfaces of the aeroshell are completely protected by the aeroshell itself during transport to the pad and integration onto the launch vehicle.

After the landing, the "petals" of the tetrahedron-shaped lander open up into the deployed configuration (Figure 2). A camera is deployed upward on an extendable boom. The antennas and a meteorology boom are also shown. The Sojourner rover is driven off over a small ramp deployed from the petal for that purpose. Most of the lander electronics modules are inside a thermal enclosure.

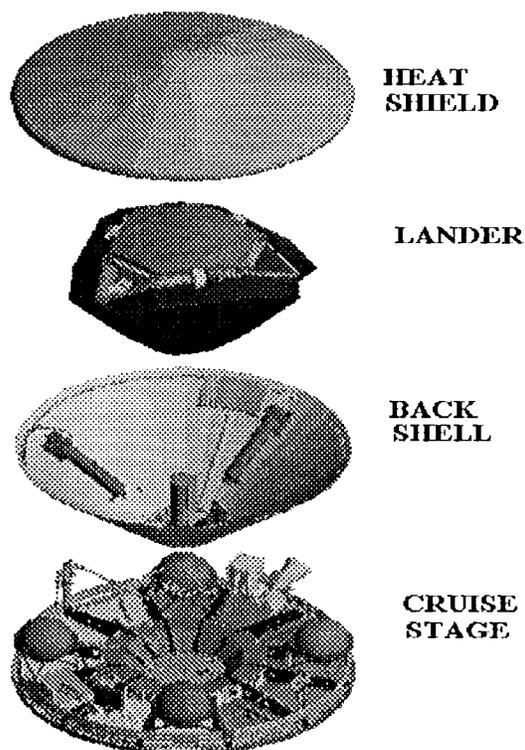


Figure 1. MPF Launch Stack (Exploded View).

However, some modules are simply mounted to the base of the lander. The top surfaces of the petals are solar arrays.

### Planetary Protection Requirements

The current planetary protection requirements relative to the microbiological cleanliness for a landed mission to Mars are as follows:<sup>5</sup> The spacecraft and its payloads shall be assembled and maintained in class

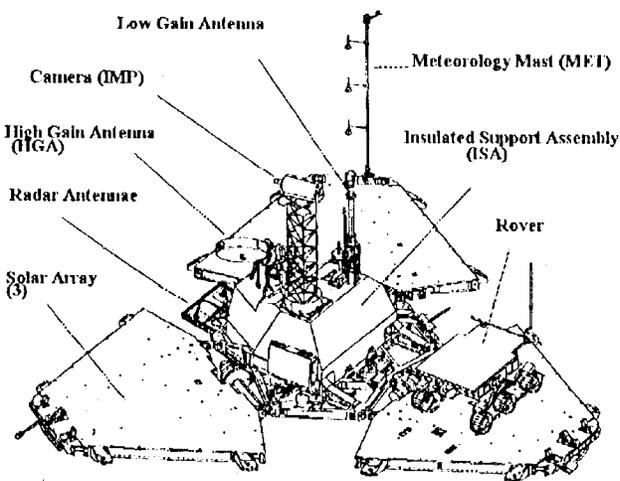


Figure 2. MPF Lander in Deployed Configuration.

100,000 (operational) or better clean rooms, with Viking Project type (stringent) controls and procedures. On "exposed" surfaces,<sup>6</sup> the average density of aerobic spores must not exceed 300 spores/m<sup>2</sup>, and the total number of aerobic spores must not exceed 3x10<sup>5</sup> spores. The two limitations on spores apply only to surfaces that have a credible chance of contaminating Mars. These requirements on spores, or burden in planetary protection notation, are fairly new regulations, first applied to Mars Pathfinder. The activities to comply with these requirements are the real subject of this paper.

Note that sterility is *not* required. The intent is a reasonable level of assurance, specifically a spacecraft as microbiologically clean as the Viking Lander was prior to its terminal sterilization<sup>7</sup> process.<sup>8</sup> The terminal process for the Viking Lander addressed a much more severe requirement; all burden (even encapsulated) was then accountable.

### APPROACH

#### Accountable Surfaces

An important PP issue for the MPF flight hardware is the separation of free surfaces, both external and internal, into the two categories: those for which the surface microbial spore burdens must be accounted and those which do not count against the PP burden requirements. In addition, some otherwise accountable free surfaces were specially exempted from burden accountability. The cruise stage was exempted on the basis of an analysis that shows Mars atmosphere entry heating to be sufficient, per the relevant PP parameter specification,<sup>9</sup> to cause (absolute) sterility. A simpler, worst-case analysis also showed that the external surfaces of the aeroshell (heat shield and back shell), including a single ply thermal blanket on the outside of the heat shield will also be heated sufficiently to confer sterility.

All of the other surfaces of the entry vehicle: the interior of the aeroshell and its internal thermal blankets (multilayer insulation or MLI), the parachute, the parachute canister, the bridle, the back shell interface plate (BIP), the RAD rocket motors and their MLI, and other miscellaneous small surfaces, are "exposed" surfaces.

The largest structure mounted on the Lander is the Insulated Support Assembly (ISA). The majority of the electronics of MPF (and a large total free surface area) is located inside the ISA, which provides thermal protection. The ISA was carefully sealed to prevent heat leaks and particle transport. A 3" diameter<sup>10</sup> HEPA filter was incorporated into the ISA depressurization vent. Thus, all surfaces inside the ISA are not "exposed."

The largest structural components of the Lander itself are the base and side petals. With the single exception of the part of the top surface of the base petal enclosed by the ISA, all surfaces of the structure of the Lander are "exposed." This approach was conservatively applied to the multiple layers in the detail of the underside of the petals, because all the layers are either fabric and/or do not completely enclose the inboard volume. For example, the air bags were not considered sufficient as a petal enclosure, that could exempt all of the inboard surfaces of the petals.

Other major "exposed" surfaces on the Lander are the outside of the ISA, the solar arrays, the air bags, the thermal blankets, the antennas, the rover ramps, the cables, and the science instruments. The surface area of all of the plies of the air bags was considered "exposed" because of the likelihood of tearing during even a nominal impact. Similarly, the surface area of all of the plies of the thermal blankets was considered "exposed," but because of possible weathering on Mars during the time period of PP interest. For the same reason, aluminized tape used to wrap the wire bundles (cables) outside the ISA was deemed inadequate to exempt the wire bundles. The surface areas of the (insulation of the) individual wires were considered "exposed." Due to lack of documentation on the venting of the two pyro-switching assemblies, their interiors were also considered "exposed."<sup>11</sup> Finally, the radar altimeter electronics module, which has an oversized vent, was also fitted with a small HPA filter. Thus, its internal surfaces are exempt.<sup>12</sup>

On the Sojourner rover, all surfaces external to the warm electronics box (WEB) are "exposed." In addition, the exterior of components located inside the WEB (and the inside of the WEB wall) were also considered "exposed" because there are too many penetrations and vents to confer an exemption for the design as flown.

### Contamination Control Procedures

The approach to burden reduction and control for MPP consisted of: alcohol (wipe) cleaning; dry heat microbial reduction; recontamination control; general contamination control, as required by PP and as augmented for specific hardware and operations in manufacture or Assembly, Test, and Launch Operations (ATLO); and special environmental control. The first two items are methods for burden reduction after the fact to a value acceptable to PP. The control measures are intended either to lower the rate at which the burden on an exposed surface increases or to absolutely prevent any increase (e.g., recontamination control after a final assay).

In general all "exposed" surfaces of flight hardware were either cleaned or processed by dry heat.<sup>13</sup>

The exceptions comprise a few small areas, typically those that could withstand neither heating nor cleaning. The burden of these exceptional surfaces is estimated per PP parameter specifications and so book kept. The exterior surfaces of items that were processed by dry heat and of necessity later exposed, were additionally cleaned prior to installation.

All free surfaces of flight hardware, except as noted above, were cleaned before the installation of the hardware. The rover was cleaned by a "precision cleaning" process that involves freon vapor degreasing. All of the other surfaces of the MPP Lander that were cleaned were wiped with sterile alcohol and sterile wipes. Ethanol was exclusively employed during ATLO. In fact, only ethanol may have been used at other times, despite isopropyl alcohol possessing some sporicidal effectiveness. (Ethanol has virtually no effect on spores.)

Seventeen different MPP assemblies and components were dry heat processed. The rationale for selection was typically large surface area (e.g., the parachute and thermal blankets) or impracticability of cleaning by wiping (e.g., solar arrays, wire harnesses, and even separation nuts). The selected process conditions for MPP were a duration time  $t$  (hours) for a range of minimum temperatures  $T$  (C) in the processed hardware on the range 110C to 125C:

$$t = 5 \times 10^{(125-T)/21}$$

The parameters were conservatively based on the relevant PP parameter specifications.<sup>14</sup> For example, a minimum process temperature of 110°C was established to ensure that the lowest temperature in the processed hardware is in fact > 104°C, as required. This process will provide a reduction in spore burden by a factor of 10<sup>4</sup>, the maximum that may be claimed per the specifications, without verification. Only a pre-process assay is required for PP.

The PP parameter specifications for dry heat microbial reduction also require a maximum *absolute* humidity, corresponding to 25% RH at 0C at 1 atmosphere pressure (i.e., STP). This expression of the absolute humidity reflects the implementation for the Viking terminal sterilization process.<sup>15</sup> The specifications do not explicitly note that the technical issue that must be solved by an acceptable alternative process is to maintain the absolute humidity. The Viking process accomplished this directly. This issue is crucial for large surfaces.

The facility for the Viking dry heat process was not available to the MPP Project. However, an alternative approach, a vacuum technique, has been devised that

properly maintains the absolute humidity at the process temperature, including the removal of any water *released from the item being processed* to the extent necessary. In this technique, a standard pressure gauge is used to monitor a modest vacuum 1.15 torr, or less, maintained by a roughing pump. This is a conservative parameter, based on 25% of the saturation vapor pressure of water at STP. The allowed partial pressure *increases* at the higher process temperature. The total pressure represents an upper limit for the partial pressure of water vapor.

In addition, some of the hardware items were dry heat processed in (high) vacuum chambers (e.g., thermal blankets). In one case (the honeycomb structure and the thermal protection system of the aeroshell) the manufacturing process itself exceeded the PP specifications.

For various reasons, some of the flight hardware (and one item of non-flight hardware) was not dry heat processed per the PP specifications; specifically the absolute humidity was not controlled. For these items, the post-process microbial burden had to be established. The reduction factor cannot be inferred from the process, as it may be for a conforming process.

The parachute was processed in a sealed (flight) overpack that had been purged with dry nitrogen gas prior to sealing. However, the water expected to be released from the extensive surface area of fabric during heating into a small volume would easily violate the humidity requirement. In order to establish the post-process burden, worst-case pieces (trimmed pieces where sewing and cutting by hand had occurred) of the manufactured units were collected for both pre-process and post-process assays. This proxy approach also demonstrated that the special contamination control, in an uncontrolled environment, that had been implemented by the manufacturer was very successful. The pre-process burden density ( $3\sigma$ ) was only 172 spores/m<sup>2</sup>. Post-process the burden density ( $3\sigma$ ) was less than 1 spore/m<sup>2</sup>. The approach also demonstrated that the humidity control is vital to the process: the reduction factor was only about 500 rather than the 10<sup>4</sup> (or better) expected for the standard process.

The engineering model (EM) air bag unit was heated without any humidity control by the manufacturer. Because the EM air bags were to be used in the deployed lander system thermal test (STV-2), in which they would contact the rover and other lander flight hardware, they were assayed (sampled at the manufacturer's location). The result of this pre-process assay, 10<sup>3</sup> spores/m<sup>2</sup>, showed that even a very poor reduction of a factor of ten would eliminate any real possibility of contaminating the lander during the test. The same result, which is much less than the 10<sup>5</sup> that is specified<sup>16</sup> as the worst case for uncontrolled manufacturing,

was used to establish a reasonable value for the flight unit. This value is not unusual. The protected surfaces of items assembled from multiple plies of stock material tend to have low burden density because the stock is typically clean. However, the talc inside the innermost lining, used to insure slippage during deployment was found to be very contaminated (on the EM unit). Therefore the talc supply for the flight unit was baked at a very high temperature for several hours, and shown to be virtually sterile on a later assay of a sample. (Two 0.1 g samples produced zero spores). The flight unit was processed per the specification.

The radar altimeter antenna was also processed without any humidity control. Here the process was extremely long and hot (125C for 48 hours), for which at least a factor of 10<sup>2</sup> reduction may be safely assumed.<sup>17</sup> Hence the surface burden density in the interior of the radar altimeter antenna is taken to be 10<sup>3</sup> spores/m<sup>2</sup> (down from 10<sup>5</sup>).

The strategy during the earlier phases of ATLIO at the Jet Propulsion Laboratory (JPL) was to periodically clean the flight hardware and to maintain it in a clean condition, but then not necessarily as clean as required for launch. Status assays were also performed during the earlier phases. This approach provided practice in cleaning and recontamination control. The status assays confirmed early in ATLIO that alcohol wiping was effective toward meeting the surface burden requirement. Successive status assays like the pre-ship and post-ship assays provided a means to isolate potential contaminating events.

At Kennedy Space Center (KSC), the general approach to the prevention of the burden increasing on an exposed surface was the SALT-2 clean room and the personnel garment and glove requirements enforced. For surfaces previously cleaned, further exposure to the SALT-2 intramural environment was minimized. Typically the hardware was draped as often as possible. The lander remained as long as possible in the extra-clean anteroom within SALT-2. Surfaces were cleaned for the last time and assayed at last physical access during assembly. As possible (access for assembly excepted), "remove before flight" covers were used to protect these surfaces if a contamination access still existed and also to protect the surface of the lander solar arrays, which had been dry heat processed and already assayed by proxy.

All ground support equipment and non-flight hardware was cleaned to an expected, but unverified, cleanliness of about 300 spore/m<sup>2</sup> by alcohol wiping. Special attention was given to non-flight hardware that came into contact with the lander or the aeroshell interior. A spot assay on the lander work stand at SALT-2, where some contamination could be seen, did yield one swab with 39

spores and a verification swab (KSC) with 4 spores. This was an exception not expected to represent the cleanliness of the work stands. In any event, contamination was very unlikely to transfer from the work stand to unprotected surfaces after they were assayed for the burden at launch.

### Assay Procedures

In general, the procedures employed to assay surface burden were similar to the methods employed to assay spores on the Viking lander before its terminal sterilization. The sampling technique employed both sterile swabs and wipes (clean room cloths), dampened with distilled water. Wipes were used preferentially on large flat areas to obtain better statistics with fewer microbiological assays. The microbiological assay procedure featured: sonication of the sample with sterile distilled water, heat shock (80°C for 20 minutes), and aerobic incubation (at 32°C for 3 days) in trypticase soy agar (TSA). The number of spores was taken to be the number of colony-forming units.<sup>18</sup>

The calculated (mean) burden density  $B$  then is  $N/A_s$  (spore/m<sup>2</sup>), where  $N$  is the number of spores found and  $A_s$  is the area sampled. An upward correction was necessary to account for the fraction of sonicate actually plated (.8 for the swabs and .25 for the wipes). It is important to estimate a standard deviation  $\sigma_B$  for this mean value so that a (larger) value can be derived and associated with a level of confidence (that the burden density on the entire area  $A_0$  will not exceed the mean value of the assay). For this purpose a second burden density value  $B_{max}$  was estimated at the .999 level of confidence ( $3\sigma_B$  or equivalent), although the PP requirement is not specific on this point. The variance in the burden density due to the statistics of the fractional sampling and due to the enumeration of the number of spores far exceeds the uncertainty in the "measurement" of the sampling area. Therefore, the latter contribution to  $\sigma_B$  was neglected.

Two circumstances must be considered: the case where the number of spores counted is small (zero or one); and the case where the number of spores is greater than one. For swabs, the first case was treated by Poisson statistics, because the probability per sample of a positive sample is small and the total number of samples that *could be taken* in an area  $A_0$  is large. The Poisson mean number of spores (expected) on  $A_0$  is given by  $\Lambda_0/A_s$ . The standard deviation of this mean is its square root. Thus for a group of swabs used to sample an area  $A_0$ , where the results were zero or one spore,

$$\sigma_B = (1/A_0)\sqrt{A_0/A_s} \quad \text{or} \quad 1\sqrt{A_0/A_s}$$

As a very conservative measure, although the mean burden

density is formally zero for a group of swabs with zero positives, its value was taken *as if* one spore had been found. For wipes, the first case was treated by Gaussian statistics, because the total number of samples that *could be taken* in  $A_0$  is small (typically one or two). The relatively large fraction sampled is the advantage of wipe sampling. The standard deviation of the mean burden density was calculated directly, as though one spore was found (even if none were). For convenience and for a minor increase in conservatism<sup>19</sup>

$$\sigma_B = 1/A_s$$

was used instead of the previous formula. Thus for a single standard .25 m<sup>2</sup> wipe sample with either zero or one spore found,  $\sigma_B$  is 16 spores/m<sup>2</sup> (because of the .25 pour fraction!). For either swabs or wipes, the second case ( $N>1$ ) was treated analogously to the wipe results as described above, but with the actual number of spores found. For the assumed Gaussian distribution in  $N$ ,  $\sigma_N$  is  $\sqrt{N}$ . Thus

$$\sigma_B = \sqrt{N} / A_s$$

In all cases,  $B_{max}$  was taken conservatively to be the formal mean plus  $3\sigma_B$ .

### RESULTS<sup>20</sup>

The results of the MPF bioassays have shown that alcohol wiping is an effective cleaning technique, that even nonstandard heat processing is a useful microbial reduction technique, and that the status assays were useful for early ATL.O. The results of intermediate status sampling and bioassay of the surfaces have demonstrated clearly that such cleaning is adequate to reduce spore burden density below the 300 spores/m<sup>2</sup> requirement. For example, a lander petal mockup in the fabrication shop assayed at 1600 and a non-flight rover, 900 spores/m<sup>2</sup>. A cleaned flight petal per the pre-ship assay was less than 40 spores/m<sup>2</sup>; the entire flight rover after precision cleaning yielded only 3 spores (on about 1 m<sup>2</sup>). Even the occasional surface that was found to be moderately contaminated during ATL.O at KSC, such as one side petal thermal blanket, which had a burden density of  $1.5 \times 10^3$  spores/m<sup>2</sup> as installed (90 spores on one wipe), *showed zero spores on a wipe assay after cleaning* (comparable to the other three sides).

The calculated burden density and burden for the MPF spacecraft at launch are shown in Table 1. The average microbial spore burden density and the total microbial spore burden on the accountable ("exposed") surfaces at launch, were  $12.4 \pm .8$  spores/m<sup>2</sup> and  $2.4 \times 10^4 \pm .16 \times 10^4$  spores, respectively, on an area of  $1.9 \times 10^3$  m<sup>2</sup>. For those accountable surfaces only (an area of about 321 m<sup>2</sup>) that were cleaned by alcohol wiping and later assayed, the

Table 1. MPP Assay Results Summary

Surfaces Measured/Estimated	Spore Burden Density (spores/m <sup>2</sup> )	Spore Burden (spores)
All "Exposed" Surfaces <sup>21</sup>	12.4 ± .8	2.4x10 <sup>4</sup> ± .16x10 <sup>4</sup>
All Assayed "Exposed" Surfaces	42.6 ± 3.1	1.37x10 <sup>4</sup> ± .10x10 <sup>4</sup>
Exterior Surfaces Only <sup>22</sup>	34 (3σ = 191)	1.3x10 <sup>3</sup> (3σ = 7x10 <sup>3</sup> )

average microbial spore burden density was 42.6 ± 3.1 spores/m<sup>2</sup> ("three-sigma" value 52 spores/m<sup>2</sup>). The spore density increased because of the exclusion of large surfaces that were dry heat processed to very small densities. The average spore density for exterior surfaces only (cleaned by alcohol wiping and later assayed) was 34 spores/m<sup>2</sup>, with a "three-sigma" value of 191 spores/m<sup>2</sup> (on an area of about 38 m<sup>2</sup>). This increase in the "three-sigma" value from 52 to 191 spores/m<sup>2</sup> reflects the random re-contamination of relatively unprotected surfaces in the SALT-2 nominal class 100,000 clean room (which was operated in the class 10,000 range typically, with respect to particles larger than five micrometers in size).

These data are based on 785 assay samples: 449 preliminary and status samples, 269 final samples and 67 verification samples. The latter samples were taken for an independent assay. The microbiology for the verification samples was performed by Rudy Pule and Norman Fields (Bionetics Corporation) and others on the staff of the KSC Microbiology Laboratory.

## CONCLUSIONS

As determined by the procedures described in this paper, the "three-sigma" values for aerobic spore burden density and the total aerobic spore burden on the accountable (PP "exposed") surfaces at launch, were 14.9 spores/m<sup>2</sup> and 2.9x10<sup>4</sup> spores, respectively. These results demonstrate the compliance of the Mars Pathfinder Project with the planetary protection requirements on microbiological cleanliness.<sup>23</sup>

Because of the basis for the new planetary protection regulations for Mars landed missions, a comparison with the analogous results for the Viking (1975) Lander exterior surfaces prior to the Lander's terminal sterilization process is of interest. The comparison is favorable for MPP. The average aerobic burden density for the external surfaces of the MPP Lander (and the aeroshell) that were not dry heat processed was 34 spores/m<sup>2</sup>, with a "three sigma value" of 191. The (aerobic) spore burden density ranged from 22 to 230 spores/m<sup>2</sup> on the Viking Landers' exterior surfaces<sup>24</sup>.

These results also demonstrate that the approach taken by the Mars Pathfinder Project is sufficient in general to meet the NASA planetary protection requirements for a Mars landed mission. As intended by the writers of the specific regulations, any NASA Mars landed mission may comply by reasonable procedures: alcohol wipe cleaning, selected dry heat microbial reduction of large surface area assemblies prior to spacecraft integration, and a rigorous, but not unusual, spacecraft contamination control program.

## ACKNOWLEDGMENTS

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## REFERENCES & NOTES

1. Planetary Protection Provisions for Robotic Extraterrestrial Missions, NASA Policy Guide NPG 8020.12B (release pending).
2. Biological Contamination Control for Outbound and Inbound Planetary Spacecraft, NASA Policy Directive NPD 8020.7E (release pending).
3. "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," in *U.S. Treaties and*

*Other International Agreements* **18**(3), pp. 2410-2498 (1967).

4. David S. McKay, Everett K. Gibson Jr., Kathie L. Thomas-Keprta, Hojatollah Vali, Christopher S. Romanek, Simon J. Clemett, Xavier D. F. Chillier, Claude R. Macchling, Richard N. Zare, "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001," *Science* **273** (5277), pp. 924-930 (August 16, 1996).

5. See Ref. 1.

6. Per the MPF PP Plan, the operational definition of an exposed surface is as follows: An exposed surface shall mean a free surface that: is external in the flight or deployed configuration, or is in no more than a single enclosure, in either configuration, which permits the transport of gas and microbial spores or which will permit such transport in a non-nominal (not mission catastrophic) landing. The purpose of this definition is to allow spacecraft modules to be vented, as all except hermetically sealed modules must be, without an accounting of all internal free surfaces.

7. The process was so named even though absolute sterility was neither assumed nor expected. To avoid confusion on this point, later workers have adopted the phase dry heat microbial reduction process.

8. See "Biological Contamination of Mars, Issues and Recommendations", by the Task Group on Planetary Protection of the Space Studies Board of the National Research Council, National Academy Press (1992).

9. See Planetary Protection Parameter Specification Sheets in *Ref. 1*.

10. Three times larger than the free vent to account for the filter's impedance.

11. conservatively despite the fact that the vents are covered by MLI so that a plenum to act as a second barrier is present.

12. The vent is really an access for adjustments; the module was not a spaceflight design.

13. except the cruise stage and the exterior of the aeroshell (back shell and heat shield)

14. See Planetary Protection Parameter Specification Sheets in *Ref. 1*.

15. In this process, a circulating dry nitrogen gas oven was employed. Relative humidity is not readily measured at the elevated temperature in the oven, as desired for an efficient process. Therefore the gas was cooled outside the heated chamber of the oven, and its relative humidity measured to infer the absolute humidity. Then the gas was dried, reheated and recycled into the oven.

16. See Planetary Protection Parameter Specification Sheets in *Ref. 1*.

17. The worst case humidity may be expected to reduce the effectiveness to about 4.5 hours with the humidity controlled.

18. Details are available as Appendix A of "Mars Pathfinder Planetary Protection Implementation Document," Project Document PF-300-3.1, JPL D-13645 (April 1996). This procedure is essentially per NIIB 5340.113, "Microbiological Examination of Space Hardware" or per the "Viking '75 Program Microbiological Assay and Monitoring Plan", where the latter is different.

19. Note that  $\Lambda_s$  is bounded by  $\Lambda_0$ ; therefore this value for  $\sigma_B$  is an upper limit. This is equivalent to the number of spores *found* being Gaussian. Then the standard deviation is the square root of the number found; in this case one (or one replacing zero).

20. More details are available in: J. Barengoltz, "Mars Pathfinder Planetary Protection Report, Part I, Pre-Launch Report," Project Document PF-300-3.2, JPL D-14035, Part I (November 1996).

21. Values shown include post-process estimates for dry heat processed surfaces, per PP parameter specifications, in *Ref. 1*.

22. Surfaces accessible after spacecraft fully assembled, including thermal blankets, with lander in deployed configuration (open petals) and aeroshell separated into heat shield and back shell.

23. See Ref. 19.

24. J. R. Puleo, N. D. Fields, S. L. Bergstrom, G. S. Oxborrow, P. D. Stabekis, and R. C. Koukol, "Microbiological Profiles of the Viking Spacecraft," *Applied and Environmental Microbiology* **33** (2), pp. 379-384 (February 1977).