Bio-Barriers: Preventing Forward Contamination and Protecting Planetary Astrobiology Instruments[1] [2]

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Abstract—A small team of engineers at the Jet Propulsion Laboratory (JPL), California Institute of Technology have developed a unique capability for protecting planetary environments that might harbor bio-signatures, as well as protecting the instruments looking for trace organic signatures of past and/or extant life. Bio-barrier materials, designs of bio-barrier structures for flight applications, and actual flight test results for missions such as the upcoming Mars Scout, Phoenix, 07 launch are discussed in this in-depth examination of both the process and steps taken to develop effective bio-barrier mechanisms for planetary environments.

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1. INTRODUCTION

In response to the FY02 National Aeronautics and Space Administration (NASA) Headquarters Announcement of Opportunity (AO) for small missions to Mars, JPL, in concert with external teams of scientists, proposed two very exciting surface missions to the Mars North Polar Cap for launch in 2007. Those two missions were Cryo-Scout and Phoenix [1, 2]. Both of these missions were planned to explore areas where there was a high likelihood of finding water-ice; and, both of these missions were to conduct subsurface sampling. Due to the likely presence of water, a building block of life, NASA required that these missions not contaminate the surface of Mars with possible micro-organisms originating from Earth. Further, if these missions were going to be looking for bio-signatures from either past or extant life, it was essential that they not sample material contaminated by Earth-based micro-organisms, which could result in a false-positive reading of Martian life-forms.

Cryo-Scout was proposed to land at 85–87 deg N latitude on the Mars North Polar Cap. The science payload on the lander deck included a surface imager, meteorology station, and ground penetrating radar (GPR). The payload also included a cryobot carrying two to three instruments for subsurface ice-column imaging and chemistry measurements. The cryobot probe was designed to melt its way through ice to a minimum depth of 10 m with the option of reaching 150 m depending on ice/clathrate composition and mission duration. The specific science goals were:

(1) Examine a vertical profile of the layered deposits in the north polar ice to reveal the range and nature of Martian climate variation, volcanic or impact events, and other phenomena encoded in the physical and chemical properties of the ice cap.

(2) Determine climate history by measuring dust accumulation vs. depth, preferably with independent dating methods.

(3) Determine present-day accumulation rates and atmosphere/surface interactions.

(4) Characterize the mineralogy of entrained particulate material.

[1] 1-4244-0525-4/07/$20.00 ©2007 IEEE
[2] IEEEAC paper #1216, Version 1, December 10, 2006

(5) Search for signs of extant or past life.

The fact that the cryobot was going to be melting as it penetrated the polar ice sheet, coupled with the goal of conducting astrobiology, drove the team to develop a unique design for the first bio-barrier since the original Mars Viking lander (i.e., which was a bio-shield built around the entire spacecraft) [3]. The barrier not only had to keep the probe free of Earth-based organic contamination once the probe was cleaned prior to launch, but also had to prevent lander deck contamination from getting into the melt column once the probe was deployed. Additionally, both the probe and bio-barrier had to be deployed once they reached the Martian surface. Figure 1 shows the final lander design of both the probe and bio-barrier in their deployed configurations.

While rated extremely high for its science return and innovative approach to doing deep subsurface sampling, this proposal was not selected. However, the work done on designing a viable bio-barrier for planetary protection/ contamination control was not lost. The proposal that was selected, Phoenix, also required a bio-barrier to protect its sample acquisition device, a robotic arm (RA). The same research in materials, structures, and mechanical design had equal application to the Phoenix arm.

Mars Phoenix was also a high latitude (65-72 N latitude) polar ice sampling mission. Although the landing site was not actually on the polar cap, it was still high enough to insure the presence of water-ice just below the regolith. Based on data from the Mars Odyssey orbiter ice mapping instrument, projected ice depths ranged between 0.4 to 0.6 m. The robotic arm was designed to dig to a maximum depth of 1 m. Similar to Cryo-Scout, the primary science goals of Phoenix were to:

1. Image the area around the lander.
2. Image the trench sidewalls.
3. Perform meteorology measurements (MET).
4. Study the inorganic/organic chemistry of the icy regolith using microscopy, electrochemistry, and conductivity analyzer (MECA), and combined thermal evolved gas analyzer-mass spectrometer (TEGA/MS).

For this application, the team developed a bio-barrier design that encapsulat the forearm link of the robot arm such that the primary element of the arm in contact with the Martian surface, the end-effector scoop, was protected from potential lander-deck contaminants prior to being deployed. While simple in concept, the design team soon learned that the problem was considerably more complex than originally thought. Since the original mission proposed to use science instruments that had already been built under the Mars01 Odyssey lander project, payload mass, power, and volume were pre-defined with minimal margin. The introduction of the bio-barrier which needed to fit over the arm that was strong enough to survive launch and entry loads and safely deploy, stressed the limits of what little margin was left. The final lander configuration showing the robotic arm and bio-barrier in their stowed configuration on the deck is shown in Figure 2.

The design, development, and test of the first true bio-barrier since Mars Viking are the focus of this paper. The results of this extensive research and development activity have far reaching impacts on other Mars missions as well; namely, the Mars Science Laboratory (MSL) and the future Astrobiology Field Laboratory (AFL). Some of the early design results are also discussed as part of this paper. The following section provides a more detailed discussion of the planetary protection and contamination issues highlighted in the previous paragraphs.

2. PLANETARY PROTECTION/CONTAMINATION

Planetary Protection

The bio-barrier serves two purposes for planetary instruments, 1) planetary protection (PP), and 2) contamination control (CC). These two requirements may be similar but are derived from very different higher level requirements.

The purpose of PP requirements is to control terrestrial microbial contamination on extraterrestrial Solar System bodies, and to control contamination of the Earth and Moon by extraterrestrial Solar System material returned by such missions. The NASA Headquarters PP Officer establishes PP requirements based on recommendations set by the Committee on Space Research (COSPAR), part of the International Council for Science. The NASA PP Officer then imposes the PP requirements on the JPL planetary missions. Since they are based on international agreements, such requirements cannot be waived by missions. PP mission categories relevant to this bio-barrier research as defined in NASA Procedural Requirements (NPR) 8020.12C [4] are summarized as follows:

Category IV – Lander or probe missions with significant interest relative to the process of chemical evolution and/or the origin of life, or for which scientific opinion suggest a significant chance of contamination, which would jeopardize biological experiment or exploration.

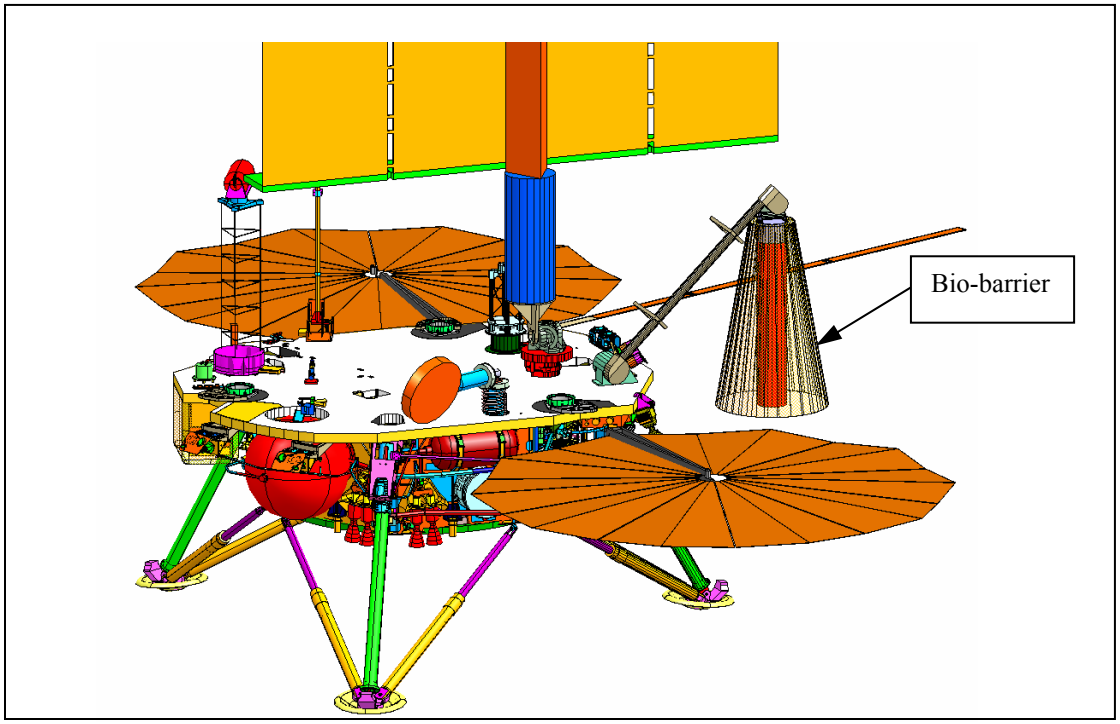

Figure 1. Cryo-Scout Probe with Bio-Barrier

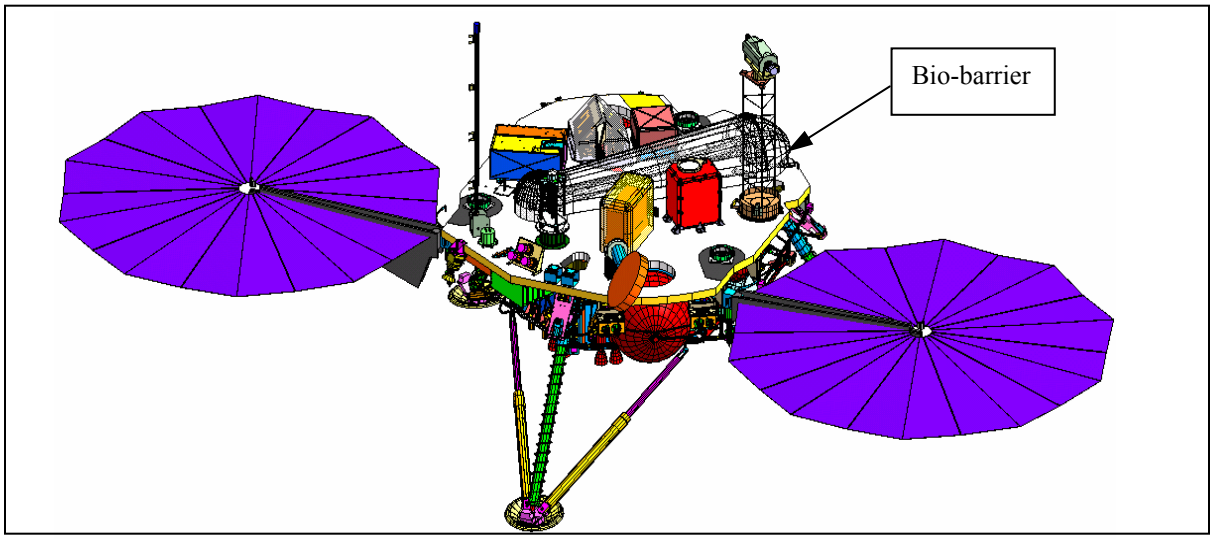

Figure 2. Phoenix RA Bio-Barrier on Lander

Category IV above is further subdivided into three categories:

Category IVa – Comprises lander systems not carrying instruments for the investigation of extant Martian life. [Note that a lander could be Category IVa while another element on the lander (such as a robot arm) may be IVb];

Category IVb – Comprises lander systems carrying instruments designed to investigate extant Martian life;

Category IVc – Comprises lander systems that investigate Martian special regions; a special region is defined as a region within which terrestrial organisms are likely to propagate or a region which is interpreted to have a high potential for the existence of extant Martian life forms.

The IVb and IVc categories are likely to require bio-barrier technology to enclose portions of a lander that reaches a special region on the Martian surface. Such portions of the lander must be microbially reduced to meet the PP bio-burden requirement, then protected inside the bio-barrier from recontamination during subsequent handling and launch environment.

Contamination

The purpose of CC is to address molecular and particulate contamination that could be detrimental to the required operation, reliability or performance of a part, component, subsystem or system, including science instruments looking for life processes. This implies that mission CC requirements are dictated, at least partially, by the type of hardware, and therefore are mission-specific. Depending on the stringency of the CC requirement, bio-barrier systems developed under this task may, or may not provide adequate CC protection. For example, a PP bio-barrier requires the obstruction of 99.97% of all particles or organisms greater than 0.3 μm [equivalent to a high efficiency particulate air (HEPA) filter]. If an instrument has sensitivity to particles smaller than 0.3 μm, a PP bio-barrier will not provide the required CC protection. It should also be noted that since CC requirements, unlike PP requirements which are NASA-driven, are mission-driven and they can be changed by the project and science teams as necessary.

3. Advanced Cleaning and Contamination Control Techniques

Microbial reduction to meet PP requirements may be accomplished by any process approved by NASA. Currently, the only approved process is the application of dry heat per NASA Procedural Requirements (NPR) 8020.12C. The process conditions for dry heat microbial reduction (DHMR) are adapted from the PP specifications [4]: "D-Value for Bio-burden on Exposed Surfaces", "D-Value for Bio-burden on Mated Surfaces", and "Temperature Dependence of D-Value" in NPR 8020.12C. The selected process conditions are a duration time t (hours) for a range of minimum temperatures T (°C) in the processed hardware on the range of 110°C to 125°C [4]:

$$t = 5 \times 10^{(125-T)/15}$$

These requirements will cause a reduction in burden by a factor of 10^4, the maximum that may be claimed. The D-Value specifications also require a maximum absolute humidity, 1.2 μg of water vapor per cubic centimeter of "head space" (corresponding to 25% relative humidity [RH] at 0°C at 101.33 kPa (1 atmosphere) pressure, and 5.21% RH at 25°C and the same pressure) [4].

Because DHMR temperature may not be compatible with hardware requiring microbial reduction, alternative methods may be proposed. These methods include chemical or radiation techniques, or various combinations of these techniques with heat. This study focuses on developing a bio-barrier technology that is compatible with both DHMR and hydrogen peroxide (H_2O_2) vapor exposure for microbial reduction, a process currently being developed and going through a qualification program at JPL. Because there are known incompatibilities between hydrogen peroxide and certain materials, a series of compatibility tests are being conducted on materials commonly used in space flight hardware in conjunction with the bio-barrier materials research. It should be noted that the CC issue of removing dead organisms is typically approached by successive cleaning and protection, however, this still remains an area of on-going research.

4. Research Results Of Bio-Barrier Development

The approach taken by the bio-barrier team was to start with understanding the combined planetary protection requirements levied on in-situ surface/sub-surface missions by NASA Headquarters and the payload contamination control requirements. While the research results reported here are based on work done under the Mars Technology Program (MTP), the proposal written to obtain the funding was driven by a pressing need to solve this problem first for the near-term Mars Scout Phoenix mission (07), with future application to follow-on missions such as Mars Science Laboratory (MSL) (see Introduction). These two sets of requirements then, formed the basis for understanding what Phoenix-specific materials to select, robustness of the structure to external loads expected for Phoenix, sources of punctures/tears, design of the bio-barrier for access/cleaning during Phoenix payload integration, and sealing. The specific areas of research, design, and testing included the following:

(1) Material selection and compatibility (relative to interaction with the science payload);

(2) Material test results (out-gassing, strength, performance);

(3) Bio-barrier structural/mechanism design for load management, sealing, environmental exposure, accommodation on lander, and deployment;

(4) Analysis of failure mechanisms.

Material Selection/Compatibility

Bio-barrier material for DHMR application and hydrogen peroxide application require distinct properties. For DHMR, the requirements are as follows:

(1) Withstand temperatures in excess of 110°C;

(2) Be electrostatic discharge (ESD) dissipative;

(3) Exhibit low particle shedding.

Additionally, for the Phoenix RA application, it was desirable to identify a material with low organics content so that it did not interfere with the organic detection function of the enclosed instrument. Tedlar was found to meet these requirements. Tedlar is a polyvinyl fluoride sheet commercially available from DuPont. It is commonly used as a laminate to protect and decorate various surfaces such as aircraft interiors and building materials, and it is known for its durability and cleanability. Although Tedlar contains organic components, the shedding rate is extremely low. Additionally, shed material is easily identifiable so that it can be calibrated out if detected by a science instrument. A 25.4 µm (0.001") thick Tedlar with coatable surface finish was selected. Extensive material properties tests were conducted to qualify Tedlar. The details of the tests are covered in the following section, Material Test Results. To meet the ESD dissipative requirement, a vacuum deposited aluminum coating was used. Tedlar purchased from DuPont was coated with 12.7 µm (0.0005") thick aluminum by Dunmore Corporation in Bristol, PA. ESD dissipative property test and aluminum particle shedding test are also detailed in the following section.

For bio-barriers that will be exposed to hydrogen peroxide for microbial reduction, the requirements are as follows:

(1) Allow hydrogen peroxide vapor to permeate through the material;

(2) Be ESD dissipative;

(3) Exhibit low particle shedding;

(4) Be 99.97% impermeable to particles larger than 0.3 µm (equivalent to HEPA)

Tyvek, manufactured by DuPont, was selected for this application. Tyvek is a spun-bonded olefin, an extremely tear resistant material commercially used in wide applications including packing and sterilizing surgical instruments. It can also withstand the temperature of DHMR; therefore a bio-barrier manufactured using Tyvek can be used for both methods of microbial reduction. Extensive material properties tests were also conducted on Tyvek, and the results are detailed in the following section.

Material Test Results

A. Tedlar Testing

The following material property tests were conducted on Tedlar:

(1) Unaltered film strength

(2) Flawed film strength

(3) Fabricated seam strength

(4) Elevated temperature (DHMR) environment

(5) Clamp adhesion

(6) Crinkle test for aluminum coating separation

(7) Exposure to extreme low temperature (LN_2)

(8) Fabricated seam test at temperature extremes

(9) Outgassing.

All tests were conducted on a minimum of two identical samples. Test results that did not meet or exceed three times the expected maximum applied load were conducted a third time. For the Phoenix RA bio-barrier, the maximum normalized force on Tedlar was calculated to be 35.7 kg/m (2 lb/in), a sum of the spring load and load from pressure differential between atmosphere inside and outside of the bio-barrier. Figure 3 shows the jig assembly used in the tests and descriptions/results of each test are as follows:

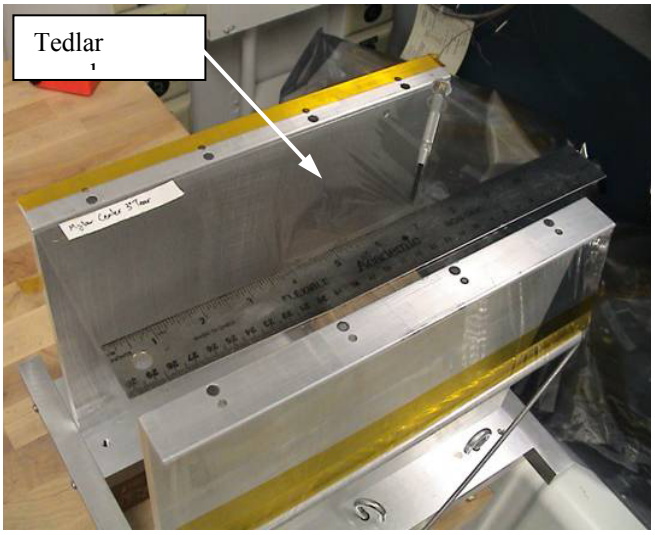

Figure 3. Typical Strength Test Configuration Showing Tedlar Sample Stretched over Jig

a. Unaltered film strength: An even force was applied to a 25.4 µm (0.001") thick unaltered Tedlar in an ambient temperature laboratory up to 32 kg (70 lb), failure, or 50% elongation, whichever came first. Result: total strength > 301.8 kg/m (16.9 lb/in).

b. Flawed film strength: The flight bio-barrier will be visually inspected for puncture and other penetrating flaws. If such damage is discovered, the flight bio-barrier will either be replaced or repaired because such damage violates its requirement. The purpose of this flawed film strength test was to determine the strength of Tedlar with surface damage without penetration. Damage without penetration may not necessitate repair or replacement of the bio-barrier as long as the strength of the bio-barrier material is not compromised. To simulate potential damage to a bio-barrier during assembly and test, three types of flaws were

introduced to the Tedlar sample, and an even force was applied to it (up to 32 kg [70 lb]) to cause failure or 50% elongation. First, a score approximately 7.6 cm (3") long was made on the Tedlar surface using a sharp blade, without penetrating through the material. Results: strength > 112.4 kg/m (6.3 lb/in.), approximately 3 times the expected maximum force of 35.7 kg/m (2 lb/in). Second, scratches of varying depth, again without penetrating through the material, were applied to Tedlar using metal wool. Result: strength > 112.4 kg/m (6.3 lb/in.). Finally, dents were created by dropping common tools (screw driver, wire-cutter, and wrench) from various heights above Tedlar. Result: strength >112.4 kg/m (6.3 lb/in.).

c. Fabricated seam strength: Tedlar pieces were sewn together with aluminized scrim reinforcement. Then Kapton tape was applied to the opposite side. The purpose of the Kapton tape is to add strength to the seam as well as sealing the needle holes. Result: strength >112.4 kg/m (6.3 lb/in.).

d. Elevated temperature environment (DHMR): A 35.7 kg/m (2 lb/in.) load was applied to the Tedlar sample while in a bake-out chamber at 110°C for 50 hours. Elongation of the sample was measured at 12%, and it was determined that this elongation will not result in inadvertent contact with the instrument inside. The pull strength of Tedlar after being exposed to 110°C for 50 hours remained the same as the unaltered sample. However, samples with a 0.318cm (0.125") tear at the edge of the sample resulted in a failure under 35.7 kg/m (2 lb/in) loading at elevated temperature. This resulted in a design change in the bio-barrier to remove loading on Tedlar in the flight bio-barrier design.

e. Clamp adhesion: Since the Tedlar bio-barrier edge will be clamped between aluminum sealing flanges, it was desirable to study the adhesion (sticking) effect of Tedlar to aluminum. Tedlar was clamped between two pieces of aluminum strips, then exposed to two 50-hour bakes at 110°C and two 1-hour soaks at –120°C. When unclamped, the Tedlar separated from the aluminum strips with no additional shear force required.

f. Crinkle test for aluminum coating separation: Flaking of aluminum coating as a result of crinkling during handling is a significant concern because of diminished ESD dissipation properties, and potential contamination on surrounding instruments from conductive particles being released. Acceptable levels for ESD dissipation is between 10^6 and 10^{12} ohm. For aluminum particle generation, particle count per Military Standard (MIL-STD) 1246C Level 300 was used as the acceptance criterion. For flight bio-barrier applications, it should also be verified that there are no open electrical conductors in the vicinity with gaps smaller than twice the diameter of largest aluminum particle released. To determine the level of aluminum particles released during bio-barrier deployment, aluminum coated Tedlar sample was crinkled 150 cycles at room temperature, 1 cycle at –85°C, an additional 5 cycles at -85°C, and an additional 20 cycles at -85°C with witness plates below it. Witness plates were removed between each cycle set, and the collected particles were counted. Particle release rate was found to be within the required level. During the crinkle test, it was noted that particle release rate was higher at the onset of the crinkling, then it was gradually decreased. The Phoenix bio-barrier material was therefore "pre-conditioned" by going through several crinkling motions, followed by a thorough isopropyl alcohol wipe before installed over the flight spacecraft. The ESD dissipation level remained acceptable at 10^5 ohm measured at 10 V, since it is expected to increase during subsequent handling. Figure 4 shows the test configuration in the thermal chamber.

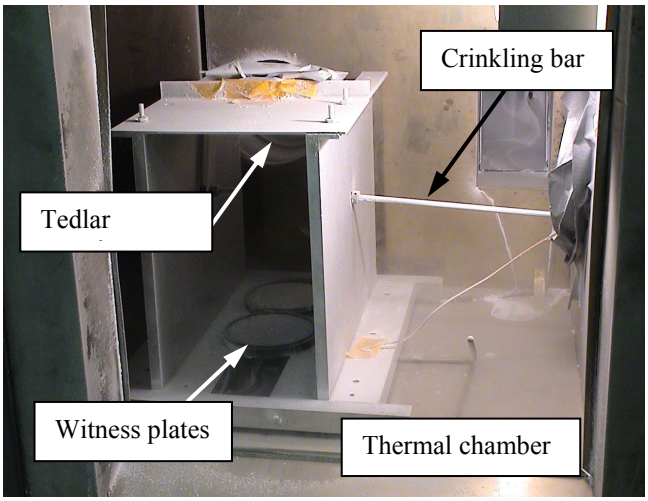

Figure 4. Crinkle Test at –85C

g. Exposure to extreme low temperature (LN_2): To simulate a worst-case low-temperature ground testing of the bio-barrier, aluminum-coated Tedlar was directly exposed to LN_2 for 60 seconds under 35.7 kg/m (2 lb/in.) loading. No cracking or tearing was observed. A pull-to-failure test after returning to ambient temperature exhibited no degradation on its tensile strength.

h. Fabricated joint test at temperature extremes: Various configurations of sewn seams of Tedlar, reinforced with Kapton and Tedlar 838 tape were loaded at 35.7 kg/m (2 lb/in.) at ambient, –85°C and 110°C. No failure occurred at ambient or –85°C; however, the tape adhesive failed (crept) at 100°C. Since this is below the DHMR temperature of 110°C, the bio-barrier support structure was designed such that Tedlar is not under tension (loaded) in stowed configuration.

i. Outgassing of Mylar burn strip: A series of tests were conducted in a thermal chamber at Mars ambient temperature/pressure to provide a measurement of condensables resulting from burn-wire operation.

A Mylar strip was burned by a wire in a chamber filled with CO_2 at Martian atmospheric pressure (1.07 kPa) and temperature (–65°C to 25°C). Witness plates were placed under the Mylar to collect condensables. Condensed out-gassed particles resulting from the burn ranged from 0.013 to 0.07 μg/cm^2 vs. the Phoenix allowable contamination science requirement of 0.1 μg/cm^2 of degraded Mylar. This test conclusively showed that the outgassing of burned materials was not an issue. It should be noted that this burn-wire method was not used for the Phoenix bio-barrier for reasons discussed later in this section.

B. Tyvek Testing

The following material tests were conducted on Tyvek:

a. Particle generation: The particle generation test was conducted under a non-controlled condition, and the results are presented here for reference only. A piece of Tyvek was crinkled by a gloved hand next to the intake port of a MetOne Laser Particle Counter on a flow-bench. As a comparison, a cleanroom wipe material was also crinkled near the particle counter. The number of particles generated from Tyvek was orders of magnitude less than the cleanroom wipe.

b. Tensile strength: Two types of Tyvek, Dupont 1422A and 1443R, were tested for ultimate tensile strength. These two were selected because they meet our basic requirements for strength, gas permeability, and ESD dissipation. Unaltered samples and bonded samples were tested (see Table 1). The bonded samples had 0.63 cm (0.25") and 1.26 cm (0.50") overlap with Y966 adhesive. All samples were exposed to vapor hydrogen peroxide prior to the tensile test. Three samples of each configuration were tested in the configuration shown in Figure 5.

Table 1. Selected Results f Tyvek Strength Test

Material	Configuration	Average Ultimate force (lb/in	kg/m)
1422A	Unaltered	10.7	191
1422A	1/6" (0.423cm) cut at edge	10.5	187
1422A	0.25" (0.635cm) bondline	1.3	23.2
1422A	0.50" (1.27cm) bondline	1.6	28.6
1443R	Unaltered	11.2	200
1443R	1/6" (0.423cm) cut at edge	11.3	201
1443R	0.25" (0.635cm) bondline	1.8	32.1
1443R	0.50" (1.27cm) bondline	1.7	30.4

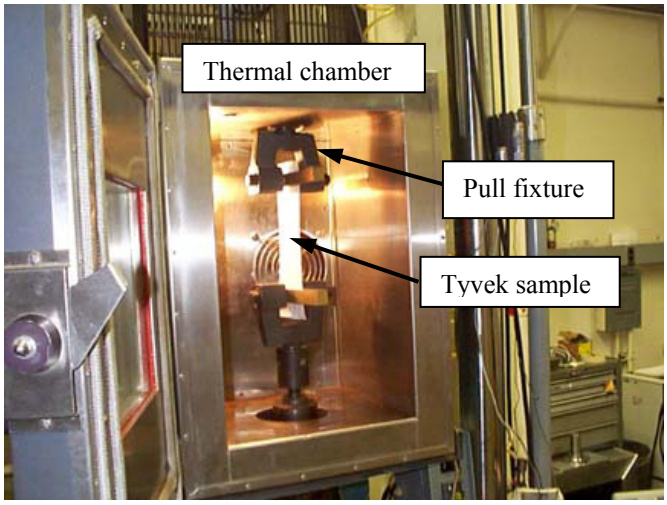

Figure 5. Tyvek Tensile Test in Thermal Chamber

A. ESD dissipation: Both Tyvek parts are manufactured by DuPont as ESD dissipative. However, due to manufacturer's proprietary reasons, the exact process of how the ESD dissipative property is achieved was not available. To ensure that this property is not compromised by handling and cleaning, ESD dissipation was measured after crinkling, 150 cycles of isopropyl wipe, and a 1-hour soak in isopropyl. ESD dissipation was measured in four different places of each part type. All cases, including the unaltered Tyvek, met the JPL requirement of 10^6 to 10^{12} ohm.

C. Compatibility Between Hydrogen Peroxide and Commonly Used Flight Materials

An extensive testing of approximately 90 common flight materials and hydrogen peroxide was conducted by JPL in 2001 [5]. Several materials were found to be incompatible. More recently, under a separately funded JPL task, a study has been conducted to revisit the hydrogen peroxide exposure profile (temperature, duration, pressure, hydrogen peroxide concentration) used in 2001. This recent study showed that a lower hydrogen peroxide concentration level resulted in acceptable microbial reduction. As a joint effort between the Hydrogen Peroxide Task and the Bio-barrier Development Task, it was decided to retest selected materials that failed in 2001, as well as new materials identified using the parts list of Mars Exploration Rover. The details of the hydrogen peroxide exposure profile are not addressed in this report. 26 materials representing adhesives, lubricants, seal/gasket, honeycomb, tapes, metals, solders, carbides, HEPA filter, wires, composites, Teflon, and coatings are currently being tested. The detailed list and the partial, in-process results are shown in Appendix A.

Another test related to hydrogen peroxide compatibility was conducted to see how far hydrogen peroxide vapor penetrates through the Tyvek barrier and into the

mechanism to which it is attached. A proto-type mini-corer instrument was used for this test (see Section 5, Bio-Barrier Applications). First, the mini-corer was opened and hydrogen peroxide chemical indicator strips were attached to various parts of the interior. Figure 15 in Appendix B shows the location of the indicators. A prototype Tyvek bio-barrier was attached to the mini-corer, enclosing the coring tool, which interfaces to the mini-corer housing through a bearing race interface. The mini-corer cover was closed, and the entire instrument was carefully sealed with only the bio-barrier and tool portion exposed. This simulated the flight configuration where the cover would be designed for a tight seal to prevent intrusion of dust from the Martian atmosphere. As seen in Appendix B, Figure 15, the preliminary results show that hydrogen peroxide does indeed penetrate throughout the mini-corer. However, the colors of the chemical indicators show significantly lower concentrations (~50%) of the hydrogen peroxide at deeper locations within the housing. Future work in this study will define the exact concentration at these locations and explore the effects of these concentrations on sensitive materials. The purpose of this study is to determine whether hydrogen-peroxide-sensitive materials can be protected within an enclosure by creating a tortuous path that either mitigates exposure completely, or lowers the concentration to acceptable levels (i.e., non-destructive levels).

Bio-Barrier Structural/Mechanism Design

The actual development and prototyping of the bio-barrier structure focused on the following critical variables:

(1) Structural integrity under all load/stress sources;

(2) Understanding mass constraints;

(3) Understanding volume constraints;

(4) Understanding power constraints.

Given that the Phoenix robotic arm (RA) and electronics were inherited from the Mars01 Odyssey lander project, the volume and power envelopes were already constrained. As Figure 2 shows, the RA is stowed diagonally across the lander deck with the MET on one side of the arm, with the MECA and the TEGA/MS on the opposite side. This meant that when the bio-barrier deployed it could not cover or interfere with the operation of any of the surrounding instruments. Additionally, although there was a spare power switch on the RA electronics control boards, that power switch was limited in both the current (~1 A) and voltage (30 V) available to enable release and deployment of the barrier. The allowable mass growth above the existing RA/electronics mass was initially limited to 1 kg. These constraints became a daunting challenge. The primary derived requirements were as follows:

(1) Bag must not rupture due to vibratory loads, inadvertent contact with the scoop, or stress induced by spring-loaded rib structure.

(2) Total bag + internal structure must be light weight and not only retain its shape (i.e., support itself in the stowed configuration), but also deploy and relax to a well defined configuration.

(3) Bag deployment must not interfere with instruments in proximity to the RA.

(4) Deployment must be simple (i.e., minimum moving parts).

(5) Bag must handle rapid depressurization/ pressurization;

(6) Bag must not obscure/snag the RA or other instruments within its kinematic work envelope.

The initial approach taken to meet the above constraints and the derived requirements was to use the passive spring-stored energy of the supporting rib structure to open the bag once a tear was initiated in the top seam by a hounds-tooth mounted on the scoop. The early design had cross-ribs (made of thin spring steel), which were under tension once the bag was sealed. A Mylar strip bridged a small gap between the two Tedlar seams running the length of the arm which was in line with the scoop and deployment plane of the forearm. Mylar has the property of being extremely strong as a continuous sheet, but once punctured, only requires 13.8 kPa (2 psi) to propagate the tear. Figure 6 shows this initial configuration.

Figure 6. Bio-Barrier Prototype, Version 1

While this configuration was successful in propagating a tear, the stored spring force of the ribs was not sufficient to consistently propagate the tear the whole length of the bag. To accomplish this meant increasing the size of the ribs. Unfortunately, the mass increased considerably, and it became extremely difficult to compress the ribs while assembling the complete structure. This configuration was unacceptable from the standpoint of opening the bag and fabricating the barrier. But, once we had a working model

and had the rib mass/spring properties and the bag material strength properties, we were able to develop a high fidelity dynamic model of the bio-barrier structure. This model allowed us to quantify its kinematic and dynamic response to induced launch and entry loads to determine if we would exceed the strength of the structure, and potentially impact surrounding instruments. Figure 8 shows the results of the dynamic response model.

The results show that while the bag is a flexible structure, its mass is so low that under the maximum expected vibratory loads it translates very little in any of the critical planes (i.e., in the x–y plane parallel to the deck in proximity to other instruments).

This result, coupled with the fact that we determined that we could at least use some of the stored energy of the rib structure to assist in opening the barrier, were crucial findings.

The next option examined for propagating the tear was a burn-wire. The burn-wire configuration included use of the available power switch on the RA electronics power board, and a high-impedance/strength wire which was laminated between two Mylar layers located length wise above the RA deployment plane (similar to the passive bag configuration described above). The physics were straight-forward—the impedance of the wire was selected to match the combined voltage/current on the output of the RA power switch such that the resulting wire temperature was hot enough to melt the Mylar strip in Mars ambient pressure and temperature. Figure 7 shows the burn wire design and actual laboratory configuration.

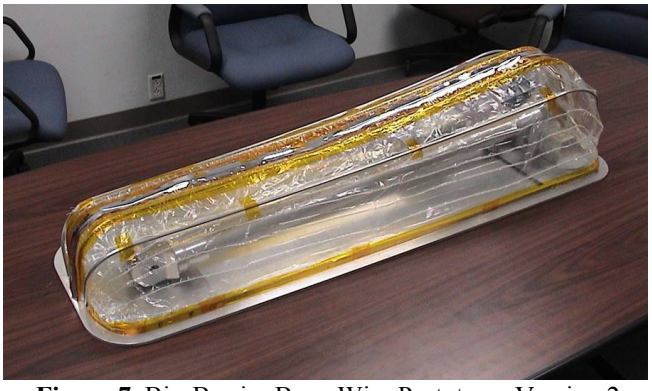

Figure 7. Bio-Barrier Burn-Wire Prototype, Version 2

It was also determined that by running the ribs lengthwise rather than crosswise, the spring tension in the ribs would provide a more constant separation force as the complete strip melted. The prototype was successful. The out-gassing of the burned Mylar strip ranged from 0.013 to 0.07 $\mu g/cm^2$ which is well within the acceptable range of the instrument. The design was reviewed by a flight review board, and while the design accommodated the tight mass requirement and minimized instrument contamination, the power margin and separation force provided by the power switch and ribs respectively were low. The review board highlighted the low margins as a significant mission risk for the flight design (i.e., if the bag did not deploy and the RA could not perform its function, the complete mission would fail) and recommended the flight project increase both the power and mass for the bio-barrier.

This decision was pivotal to being able to design the final version of the flight bio-barrier, which was sufficiently robust in meeting all requirements. Figure 9 shows the final flight configuration for the Mars Phoenix bio-barrier in its stowed and deployed configurations.

The team performed a significant number of structural/mechanical redesigns and tests over a range of environmental conditions. The material testing was summarized above. The remaining critical steps related to the final structure/mechanism components included:

(1) Develop a pin-puller release mechanism.

(2) Develop a bio-barrier sealing mechanism.

(3) Insert a HEPA-filter.

(4) Assess potential shedding of the aluminized anti-electrostatic bag coating.

The final critical step in the mechanical design to replace the burn-wire was to develop a pyro-actuated pin-puller with a large retraction spring that pulled on a cable, which in-turn slipped a series of locking pins out of their respective slots. The subsequent removal of the locking pins, coupled with the motion of flexures that pushed the bag seal flange away from the base-plate, freed the bag from its locked configuration.

The stored spring energy of the ribs then rotated the bag counter-clockwise to a compressed, deployed configuration on the lander deck. Figure 10 shows the pin-puller and cable design.

The design margin incorporated was a factor of 3× above the required release force to allow complete assembly to be successfully tested at well below the expected Mars ambient temperatures (i.e., expected operating temperature was -50°C to -70°C, with testing down to –100°C).

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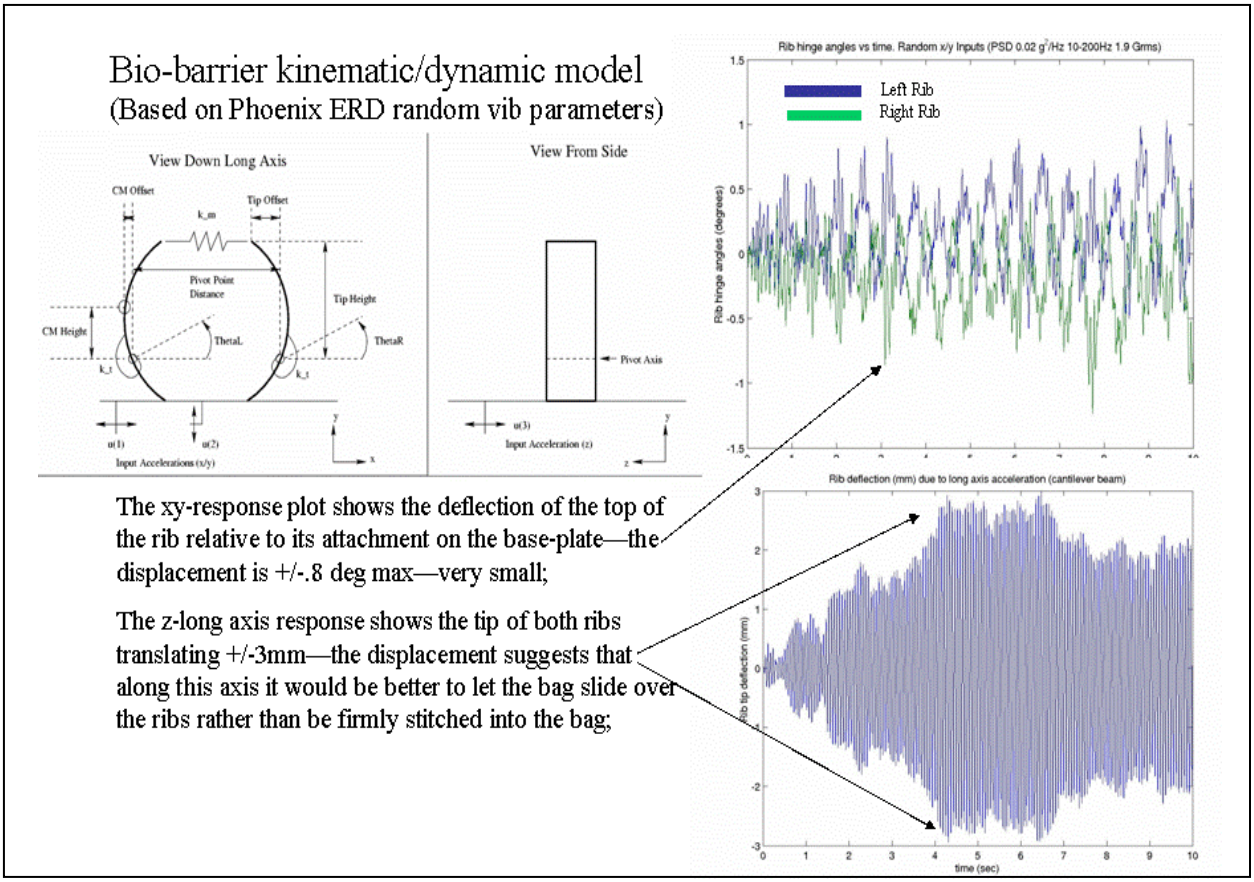

Figure 8. Bio-Barrier Dynamic Response Model

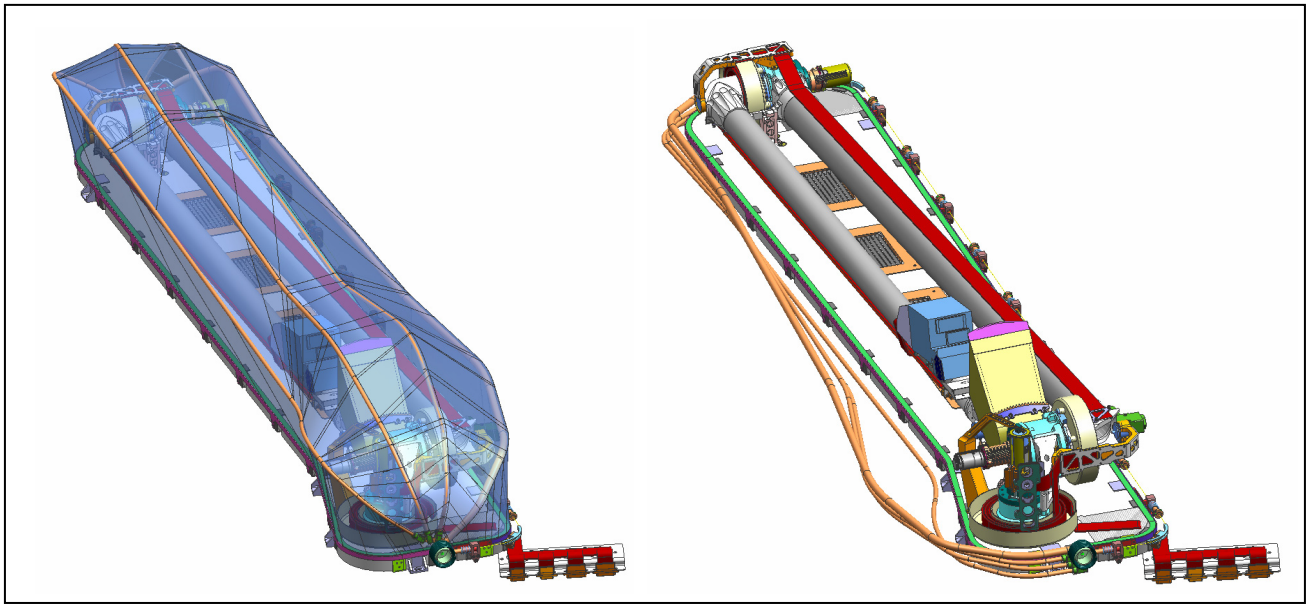

Figure 9. Flight Bio-Barrier Configuration

successfully tested at well below the expected Mars ambient temperatures (i.e., expected operating temperature was -50deg°C to –70°C with testing down to –100°C).

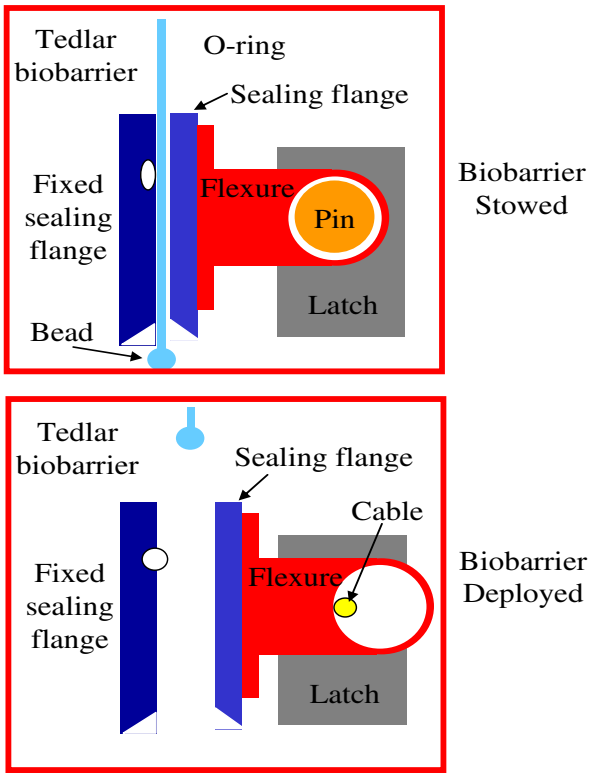

Figure 10. Pin-Puller Operation

The second critical area, the bio-barrier sealing mechanism, was essential to preventing any contamination from getting inside the bio-barrier during either launch vibratory loads or entry descent and landing loads. The bag interface to the base-plate was designed to have a female recess running around the complete circumference. The male seal counterpart (which mated to the recess) was attached to the bag flange discussed in the previous paragraph. Once engaged, the combination of the clamping force and seal then formed a "tortuous path" which prevented contaminants from migrating into the bag volume. A test fixture was designed using an actual segment of the seal, a coupon of actual bag material, and 0.102-mm (0.004-in.) shims, which separated the seal from the bag on both sides of the seal as a worst-case test of the tortuous path. Figure 11 shows the complete seal-test configuration employed in the test chamber. In the final flight design, the above hard seal/recess was replaced by a compressible seal, which provided the same functionality (see Figure 10 above).

The results were significant. Per the NASA planetary protection standards for sealing [6], the seal needed to retain 99.97% of all particles or organisms greater than 0.3 µm in size. All three tests showed "negative" (no spores detected) after swab and 24-hour incubation.

Given the above bio-load and test results, and using the criteria of ≤1 spore transported across the gap, the seal retained 99.999% of the spores. These results clearly demonstrated that the seal design adequately sealed the RA against contamination under the "tortuous-path" argument.

The third critical area, the HEPA-filter, was needed to jointly work in concert with the bag seal to keep particulates out of the interior bio-barrier volume, and allow the sealed bag to accommodate large, rapid changes in pressure during launch and re-entry into the Mars atmosphere. From a particulate-size standpoint it was determined that a HEPA-filter was the correct filter size. A subsequent flow and pressurization analysis showed that the base-plate needed to have four filters in order to accommodate the rapid de-pressurization and re-pressurization during launch and re-entry to prevent rupturing the bio-barrier. This design was tested via simulation, and significant margin was placed on the number of filters to insure the bag structural integrity did not come close to being exceeded.

The last area, shedding of the conductive bag coating due to extreme temperature excursions, was discussed in the previous section on materials testing. It became critical because the team determined that without an aluminized coating on the Tedlar material, the bag developed a significant static charge during handling. The initial test results were disturbing for two reasons:

(1) The **total** particulates released were of sufficient quantity to potentially represent shorting hazards to the RA.

(2) If enough of the coating was shed, it could degrade the conductivity of the bag and increase the chance of an electrostatic discharge (ESD) which, in turn, could damage sensors or electronics.

However, follow-up tests showed that these concerns were mitigated by first pre-conditioning the Tedlar by crinkling, followed by careful cleaning of shed aluminum particle. The Project was also able to obtain Tedlar and higher adhesion coating from the mafucaturer.

Analysis of Failure Mechanisms

The bio-barrier team not only worked through all the implementation issues associated with developing a flight quality planetary protection system, but it also examined the integrity of the design in the presence of faults. The primary sources of failure revolved around the following:

(1) Bag tears or ruptures;

(2) Bag deploys prematurely;

(3) Bag does not deploy;

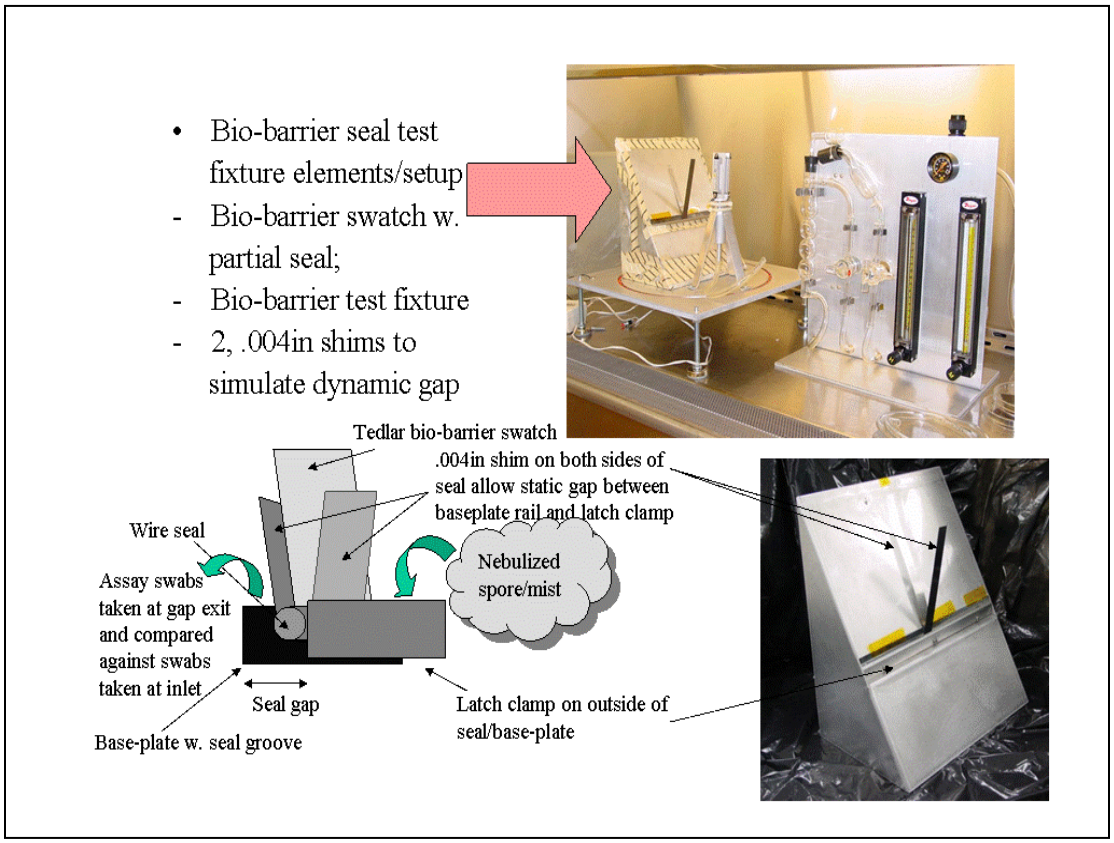

Figure 11. Bio-Barrier Seal Test Configuration

(4) Lock pins jam;

(5) Pin-puller/pyro fails;

(6) Pin-puller cable fails;

(7) Deployment torsion spring fails;

(8) Ribs/bag interferes with lander leg deployment.

Item (1) was managed by picking a Tedlar thickness which gave 3 times the strength needed to resist punctures or tears. Additionally, an RA metal cover was designed and built for use during final payload integration and test on the lander deck. The metal jig protected the bio-barrier and RA in the event tools or other support equipment (e.g., overhead crane) inadvertently intersected the RA work envelope. Item (2) was resolved by having multiple tie-down points around the circumference of the base-plate and setting the release force of the pyro/pin-puller well above the forces exerted by launch and re-entry loads. Items (3, 4, 6, and 7) were managed by adding mass to make the complete deployment chain force/torque margins (e.g., torsion springs, pin-release mechanisms, use of Teflon or dry lubricants to minimize friction in the sliding pins, and wire cable) 3–5× what they needed to be to release the bag structure. Item (5), the pin-puller pyro, was a flight device with known, proven, and tested capability, which had flown on numerous previous missions. The last item (8) was essentially a design solution coupled with empirical testing. The complete bio-barrier structure was modeled and tested in the laboratory to confirm that it always deployed to the same desired compact configuration with no interference with the lander-leg dynamic envelope.

5. BIO-BARRIER APPLICATIONS

Mars Scout Phoenix Lander

The two primary near-term applications for bio-barriers are Mars Phoenix (launch in 2007) and MSL (launch in 2009). The Mars Phoenix bio-barrier was discussed in detail in the above paragraphs. The final flight design is shown in Figure 12. It should be noted that at the close of the research activity and transfer-over to the flight implementation, the flight team continued to make refinements to the bio-barrier design to enhance its reliability. At the time of this publication, the complete Phoenix RA and bio-barrier assembly is in the process of being integrated with the rest of the science payload onto the Phoenix lander deck. Phoenix is scheduled for launch in August of 2007.

Mars Science Lander (MSL)

The current research being cnducted in support of a potential bio-barrier design and materials selection/testing for the MSL sample acquisition-sample processing and

handling (SA-SPaH) subsystem is work in progress and is, therefore, only summarized here. The most important drivers behind this application are two fold:

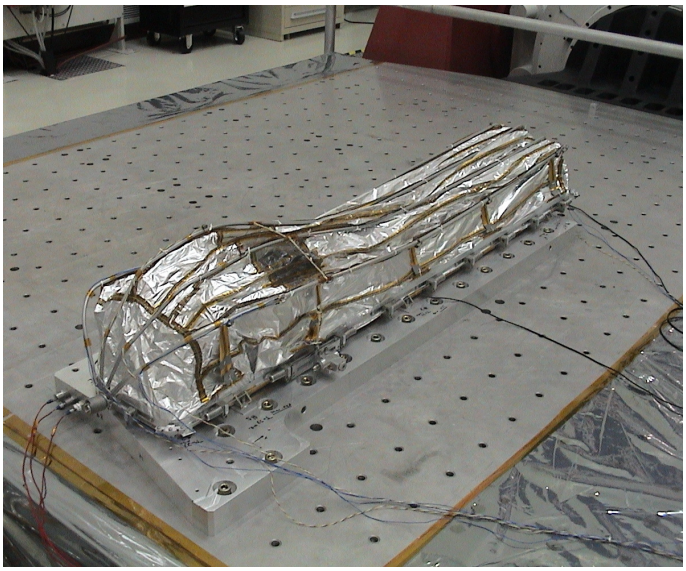

Figure 12. Phoenix Flight Bio-Barrier

First, many flight hardware, including the SA-SPaH, contain components that are not compatible with the elevated temperatures of DHMR. For such subsystems, alternative methods of microbial reduction are required. Application of vapor hydrogen peroxide was selected, and a small scale bio-barrier using Tyvek was developed which allows the hydrogen peroxide to flow through the barrier.

Second, unlike the Phoenix RA, which is only deployed once and never gets close to the lander deck where it can be contaminated, the MSL corer will need to be stowed close to the front surface of the rover deck in order to facilitate safe rover traverse after a sample has been delivered. This means that the corer will either need to be removed and placed in a sealed container between samples, or, retracted into a bio-barrier. A re-deployable bio-barrier that reseals the mini-corer between samples would allow the mini-corer to be safely deployed and retracted many times in the course of the MSL sampling mission. While the large-scale Tedlar bag worked well for the Phoenix bio-barrier, stowing it back to its closed position was a time consuming operation. This was a schedule and contamination risk every time the barrier had to be deployed during assembly and test. A small-scale, reusable bio-barrier such as the one developed for MSL would be extremely beneficial, from the standpoint of schedule savings and contamination control.

The SA has five tools/instruments on the arm turret which includes the mini-corer, Surface Removal Tool (SRT), the Surface Regolith Sampler, the Proton/X-ray Backscatter Spectrometer (APXS), and the Microscopic Imager (MAHLI) micro-imaging camera. The arm turret is predicted to weigh approximately 15 kg. The swept diameter of the turret is approximately 0.5 m. Figure 13 shows the turret and mini-corer.

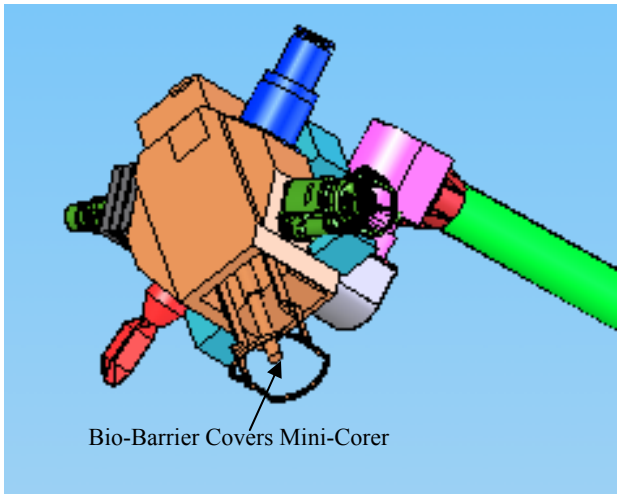

Figure 13. MSL Mini-Corer on Turret

The development of a bio-barrier mechanism for the corer on the SA-SPaH is guided by the following requirements:

(1) The bio-barrier cannot impose requirements or changes that affect the performance or deployment of the corer;

(2) The bio-barrier must be light-weight and limited to a single deployment actuator;

(3) The bio-barrier must minimize energy consumption;

(4) The bio-barrier must minimize sliding surfaces due to the low air pressure on Mars that can cause mechanisms to bind;

(5) The corer must be able to perform its function effectively even if the deployment actuator fails.

The bio-barrier design for the SA-SPaH mini-corer is deployed using a solenoid to minimize complexity and chance of actuator failure. The corer sits concentrically in the two-segment cylindrical bio-barrier. The upper cylinder contains the Tyvek cylindrical bio-barrier to prevent contamination and to facilitate cleaning. The lower cylinder consists of the mechanism to open the seal and allow the corer to acquire samples. The bio-barrier door is spring-loaded in a closed configuration to eliminate energy consumption when the corer is not in operation. The bio-barrier moving door has a ramp designed into it, which will allow the corer to forcefully push open the bio-barrier if the actuator fails. Currently a prototype has been built, and functional tests of the mechanism have been performed. Figures 14a and 14b display the Tyvek barrier and deployment mechanism in its sealed and deployed configurations, respectively. Research is continuing for small devices such as this.

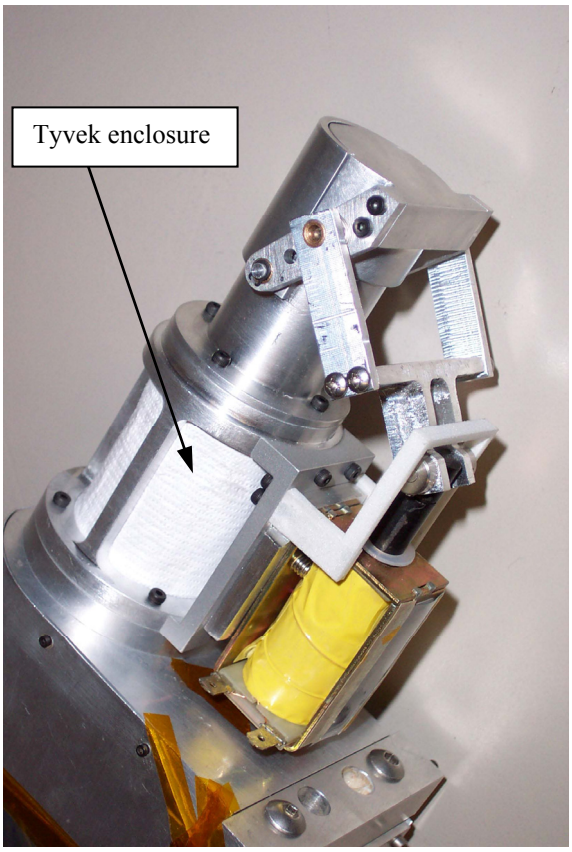

Figure 14a Tyvek Bio-barrier in sealed configuration

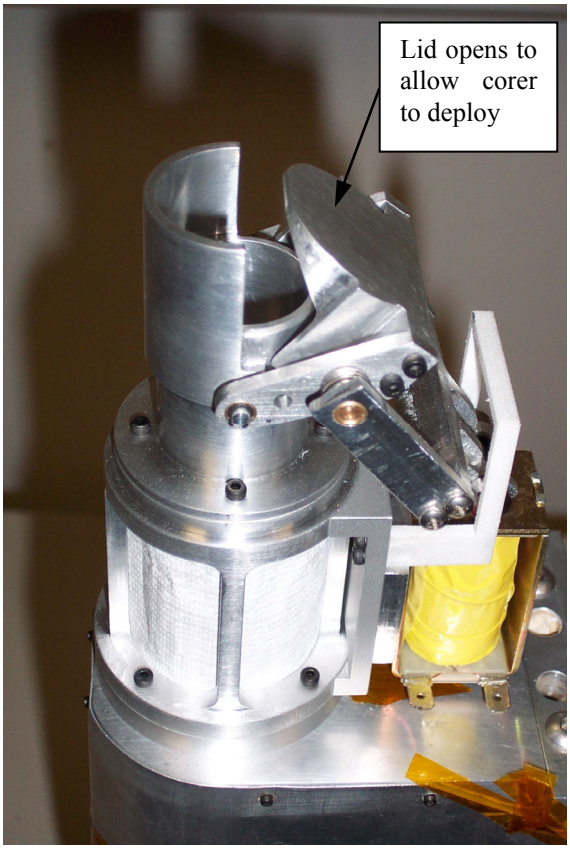

Figure 14b. Tyvek Bio-Barrier in Deployed Configuration

6. CONCLUSION/SUMMARY

An exciting milestone was reached with the closeout of the Phoenix bio-barrier research and final build of the flight unit. The authors have provided the reader with a reasonably detailed account of how the fundamental technology was developed and tested in parallel with the Phoenix RA flight system development. Perhaps the most important conclusion to draw is that insertion of any new technology, such as a bio-barrier, into a flight project requires careful planning, an aggressive schedule, and exhaustive, rigorous component and system level testing to minimize any associated risk. The approach taken in developing the bio-barrier moved away from the original Viking lander "spacecraft hard shell" and focused on protecting only the instrument elements requiring encapsulation. This approach allowed development of a very low mass, compliant, high strength, deployable barrier that met the current NASA 99.97% microbial containment requirement. This research has provided the foundation for a new paradigm for low mass, low cost, planetary protection/contamination mechanisms. Work will continue with the development and testing of the Tyvek bio-barrier and hydrogen peroxide vapor cleaning technique. In particular, attention will be given to studying and quantifying how far the vapor penetrates mechanisms, potential material degradation as a result of vapor contact, and final documentation of cleaning effectiveness and material compatibilities.

7. ACKNOWLEDGEMENTS

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BIOGRAPHY

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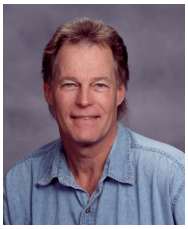

Wayne Zimmerman *is currently the Chief Engineer for the Instruments and Science Data Systems Division at JPL, CalTech, and the Co-Investigator (Co-I) for the MTP bio-barrier base technology research task. He has been involved in Mars planetary robotics and instruments through the Mars 98 MVACS lander mission and the Mars 01 Odyssey lander. He has also been developing planetary icy body in-situ science platforms for several years. Wayne led the design team for a Europa deep ice probe, called the cryobot. He was also the Chief Engineer for the subsequent research effort, which resulted in the first prototype integrated cryobot/instrument payload tested on the island of Svalbard, above the Arctic Circle. Subsequent to that successful field test, he became the project element manager (PEM) for the Mars CryoScout cryobot system, which competed in the FY02 NASA Mars Scout mission competition. He was also the acting PEM for the Mars Phoenix Scout robotic arm system, which did win and is now in its final stage of testing prior to launch in 07. He was also a co-investigator for developing a Europa icy body drop-off probe for the Jupiter Icy Moons Orbiter (JIMO). Wayne received his B.S. in Fluidics from Case Institute of Technology (Cleveland, Ohio) and his M.S. in Aerospace Systems Engineering from the University of Southern California. Wayne has been at JPL for 29 years.*

Eric Kulczycki *received a dual B.S degree in mechanical engineering and aeronautical science and engineering from the University of California, Davis, in 2004. He received his M.S. degree in mechanical and aeronautical engineering also from the University of California, Davis in 2006. He is a member of the engineering staff at the Jet Propulsion Laboratory, California Institute of Technology, where he is currently involved in planetary protection, advanced flight control for aerial robots, deep drilling, and mechanical design of various mobility platforms. He has worked on various research projects since 2002.*

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APPENDIX A – COMMON SPACE FLIGHT MATERIAL COMPATIBILITY WITH HYDROGEN PEROXIDE

Type of Materials	Materials	Test Description	Test Results		
			Average Before H_2O_2 Exposure	Average After H_2O_2 Exposure	% Degradation (-) Improvement (+)
Adhesives	Eccobond 56-C, Cat 9	Lap Shear Strength	890 psi	893 psi	+0.3%
	Eccobond 56-C, cat 11		373 psi	435 psi	+14.3%
	RTV 566		1048 psi	1109 psi	+5.5%
	BRYTE EX1516		pending	pending	pending
Lubricants	Tufram	Coefficient of Friction	pending	pending	pending
	Lubelok 4306		pending	pending	pending
	Dicronite		pending	pending	pending
Seal/Gasket	Viton 75	Tension Strength, Compression Set, Durometer Hardness A	pending	pending	pending
	Silicon 70		pending	pending	pending
Honeycomb	5056 Al Honeycomb	Flatwise Tensile	3292 lbs	3002 lbs	-9.7%
Tapes	Velcro	90 Deg Peel Strength	pending	pending	pending
	Kapton		pending	pending	pending
	Lacing Tap		pending	pending	pending
Metals	Alloy Steel 5100 Bearing	Tensile Strength	pending	pending	pending
Solders	SN60	Resistance	pending	pending	pending
	SN63		pending	pending	pending
Carbides	Tungsten Carbide	Hardness	pending	pending	pending
HEPA	Keystone M00436	Filtering Capability	pending	pending	pending
Wires	Ag-coated Cu	Tensile Strength	pending	pending	pending
	ETFE Insulated		pending	pending	pending
Composites	G11	Tensile Strength	2283 lbs	2328 lbs	+1.9%
	YS80/BTCY1		228 lbs	183 lbs	-24.6%
Coatings	TIODIZE (Ti-6Al-4V)	Optical Properties	pending	pending	pending
	Chem Conversion Coating, Class 3		pending	pending	pending
	Anodize Type 3, Class 2		pending	pending	pending

Table 2. Partial Results of Material Compatibility Tests – In-Process Study

APPENDIX B – MINI-CORER

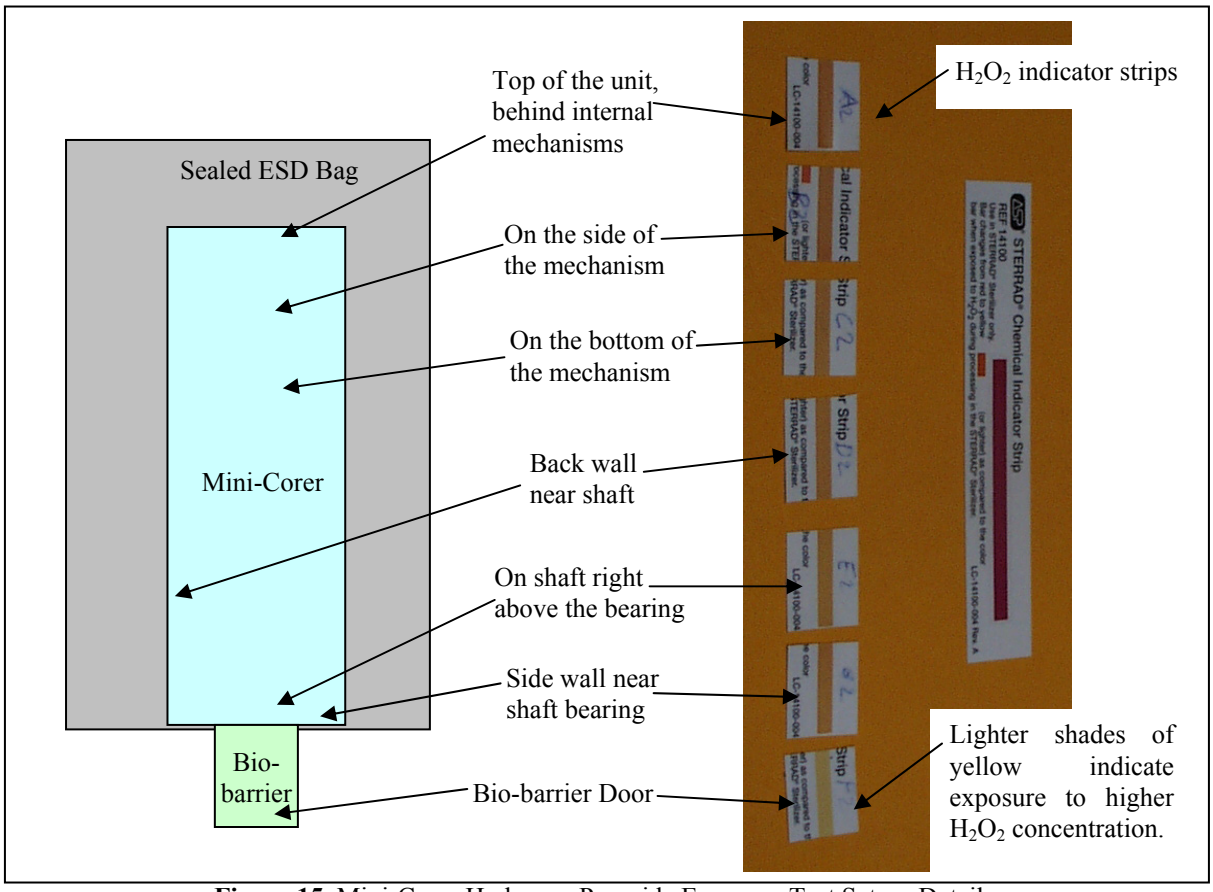

Figure 15. Mini-Corer Hydrogen Peroxide Exposure Test Set-up Detail

Figure 16. Mini-Corer Hydrogen Peroxide Exposure Test Set-up Detail