

## **MARS PATHFINDER ROVER—LEWIS RESEARCH CENTER TECHNOLOGY EXPERIMENTS PROGRAM**

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### **ABSTRACT**

An overview of NASA's Mars Pathfinder Program is given and the development and role of three technology experiments from NASA's Lewis Research Center and carried on the Mars Pathfinder rover is described. Two recent missions to Mars were developed and managed by the Jet Propulsion Laboratory, and launched late last year: Mars Global Surveyor in November 1996 and Mars Pathfinder in December 1996. Mars Global Surveyor is an orbiter which will survey the planet with a number of different instruments, and will arrive in September 1997, and Mars Pathfinder which consists of a lander and a small rover, landing on Mars July 4, 1997. These are the first two missions of the Mars Exploration Program consisting of a ten year series of small robotic martian probes to be launched every 26 months. The Pathfinder rover will perform a number of technology and operational experiments which will provide the engineering information necessary to design and operate more complex, scientifically oriented surface missions involving roving vehicles and other machinery operating in the martian environment. Because of its expertise in space power systems and technologies, space mechanisms and tribology, Lewis Research Center was asked by the Jet Propulsion Laboratory, which is heading the Mars Pathfinder Program, to contribute three experiments concerning the effects of the martian environment on surface solar power systems and the abrasive qualities of the Mars surface material. In addition, rover static charging was investigated and a static discharge system of several fine Tungsten points was developed and fixed to the rover. These experiments and current findings are described herein.

### **INTRODUCTION**

NASA is embarking on a decade long program of robotic Mars exploration to study planetary evolution, climate, potential resources and possible evidence of prior biological activity. A series of small, low cost probes, orbiters, landers and rovers will be launched to Mars every twenty six month launch opportunity culminating in a sample return mission in 2005. The first two were developed and

managed by the Jet Propulsion Laboratory (JPL) and launched in 1996: Mars Global Surveyor which will map Mars surface from orbit and Mars Pathfinder which consists of a landed spacecraft and a small rover and will perform science and technology experiments. Mars Pathfinder landed on July 4, 1997 and Mars Global Surveyor will go into Mars orbit in September. These probes will provide a wealth of martian science data, experience in operating in the martian environment and pave the way for follow-on human missions, should the nation so choose. The primary objective of the Mars Pathfinder mission, in addition to providing imaging, meteorological and surface composition science information, is to demonstrate the viability of this low cost mission concept, learn about the martian environment, how it affects exploration machinery, and how to operate, remotely, semi-autonomous equipment in that environment (Pivrotto, 1993). The lessons learned from Pathfinder will be applied in the design of the more scientifically oriented follow-on missions. Early in this program, NASA's Lewis Research Center was asked by JPL to contribute its expertise in the areas of space power technology, space mechanisms and tribology, and space environmental effects to design technology experiments to be carried on the rover that would gain valuable engineering design information in these areas. The remainder of this paper presents an overview of the Mars Pathfinder mission and describes the role of Lewis Research Center in developing Pathfinder systems and experiments.

### **MARS PATHFINDER MISSION**

Mars Pathfinder is the first mission to land on the Red Planet since Viking two decades ago and carries the first autonomous rover ever to explore the surface of another planet (JPL, 1995a), (JPL, 1995b).

Mars Pathfinder is part of the National Aeronautics and Space Administration (NASA) Discovery Program, a new generation of planetary exploration missions that perform important science investigations in shorter time and for lower cost than previous missions. Mars Pathfinder is also helping kick-off NASA's new, long term Mars exploration program, the Mars Surveyor Program, which

will involve multiple lander and rover missions launched about every two years.

The overall goals of the Pathfinder mission are to demonstrate a simple, low-cost system, at fixed price for placing science payloads on the surface of Mars at an order of magnitude lower cost than Viking; demonstrate NASA's commitment to low-cost planetary exploration by completing the mission for a total cost of \$280 million including the launch vehicle and operations, and demonstrate the mobility and usefulness of a microrover on the surface of Mars.

Pathfinder was developed and managed by JPL, and launched aboard a Delta 2 rocket December 4, 1996 on a seven month journey with a direct entry into Mars atmosphere (no parking orbit at Mars) using a Viking-derived heat shield. On July 4, 1997 Pathfinder entered the upper atmosphere of Mars at 7.6 km/sec at a 14.2° angle, reaching peak deceleration of 25 times Earth gravity at 32 km above the surface. The parachute was then deployed at twice the speed of sound at 10 km altitude further slowing the descent to a point a few hundred meters above the surface at which time braking rockets were fired, the tether attaching the lander package to the backshell and parachute was severed, allowing the lander to be dropped directly to the surface. The lander impact was cushioned by the inflation of a set of airbags, as in the artist's conception depicted in Fig. 1, which, once the system came to rest, were deflated and retracted.

Once on the surface, the lander deployed its three solar panels and the rover "Sojourner" which was attached to one of the panels (Fig. 2). The lander camera immediately proceeded to conduct a panoramic survey of the surroundings, deploy and activate its other scientific instruments, and transmit to Earth. The lander transmits engineering and science data directly to Earth at a rate of a few thousand bits per second. The rover communicates to Earth through the lander. The rover can communicate line-of-sight to the lander reasonably well up to about 500 m range but probably will not go further than about 30 m from the lander on this mission.

The primary mission is intended to last 30 martian days (sols, 1 sol = 24.6 hr) for the lander and 7 sols for the rover. The primary objectives of these system elements will be accomplished in this time. These elements could last much longer thus permitting an extended mission during which much more data could be gathered. Both elements are solar powered with the lander dependent on a daily rechargeable battery package. Since the batteries degrade with a large number of charge/discharge cycles, the lander will eventually be unable to communicate with Earth. The rover is not dependent on batteries, but will lose its communication link with Earth when the lander fails. The batteries were qualification tested to 30 days only, but could last several months.

The physical characteristics of the lander and rover are as follows: the lander mass is 325 kg, initially configured as a tetrahedral shape about one meter on a side, with the interior faces of the sides becoming the solar arrays when deployed flat to the ground, and exposing the lander instruments and bus. The solar arrays are composed of Gallium Arsenide/Germanium solar cells producing a surface daily energy of about 1080 W-hr. Computation is via a R6000 computer and 128 MB mass memory. The surface operations telemetry rate via the high gain antenna, at X-band, is 1.2 to 12 kbps with the 70 m Deep Space Network antenna.

The rover (Fig. 3) has a total mobile mass of 11.5 kg and is 75 cm in length by 32 cm wide. It has onboard autonomous navigation, using laser striping for obstacle detection. The mobility system is a

six wheel rocker-bogie suspension with each wheel independently driven by an electric motor. The command and telemetry is via a UHF link with the lander. The payload carried is fore and aft cameras, an Alpha Proton X-Ray Spectrometer (APXS), the APXS deployment mechanism, and three Lewis Research Center technology experiments to be described later. The power is provided by a Gallium Arsenide/Germanium solar array producing an energy of about 16 W-hr/sol. The interior electronics are kept warm to above -40 °C by three radioisotope heater units (RHU's). The rover computer is 80C85, 0.1 mips, 0.5 MB RAM mass storage, has a mass of 0.5 kg and consumes 1.5 W of power.

The period of surface operations time for the rover is from 10 a.m. to 2 p.m. local martian time each sol. Commands for rover movement are uplinked early each sol and the rover then autonomously conducts its assigned tasks. The rover can traverse at approximately one centimeter per second while avoiding obstacles and employing other trouble averting maneuvers. It moves only a few meters per day, probably never more than 30 m from the lander, all under the watchful eye of the lander camera.

Pathfinder arrived at Mars in the early martian fall season at a latitude of 19.5° North and a longitude of 32.8° West. The diurnal temperature variations experienced are a high (at noon) of about 0 °C and at night about -100 °C. The round trip transmission time between Earth and Mars during the primary mission is about 20 min.

### **Science Experiments**

Pathfinder's science experiments began with the lander descent through the thin martian atmosphere. The spacecraft gathered atmospheric structure data (e.g. temperature, pressure and density) and now, on the surface, meteorological data such as pressure, temperature, wind speed and atmospheric opacity will be obtained on a daily basis, adding to the Viking data base. Understanding this data is very important for identifying the forces which act on small particles carried by the wind. Regular sky and solar spectral observations using the lander camera will monitor windborne particle size, particle shape, distribution with altitude and the abundance of water vapor.

Observations of the general landscape, surface slopes and the distribution of rocks are being obtained by panoramic stereo images at various times of the day. Any changes in the scene over the lifetime of the mission might be attributed to the actions of frost, dust or sand deposition, erosion or other surface-atmosphere interactions. A basic understanding of the surface and near-surface soil properties will be obtained by the rover and lander imaging of rover wheel tracks, holes dug by the rover wheels, and any surface disruptions caused by airbag bounces or retractions.

The APXS on the rover will be used in conjunction with the color imaging (using the visible through near infrared spectral filters) by the lander imager to determine the dominant elements making up the rocks and other surface materials at the landing site. These investigations will provide a calibration (ground truth) for remote sensing observations done from orbit, such as Mars Global Surveyor. A series of small magnets on the lander are collecting any magnetic component of airborne dust, whose composition will be determined in the above manner.

New information on the rotational and orbital dynamics of Mars will be obtained using two-way X-band doppler tracking of the Mars Pathfinder location, the orientation and precession rate of the pole (regular motion of the pole with respect to the ecliptic) can be

calculated and compared to measurements made with the Viking landers 20 years ago. Measurement of the precession rate allows direct calculation of the planet's moment of inertia, which in turn is controlled by the density of the martian rock with depth.

### **Engineering Experiments**

Mars Pathfinder performs a number of significant spacecraft engineering experiments. A principal mission objective is to demonstrate a low-cost entry, descent and landing system that is capable of placing a science payload on the surface of Mars, and to demonstrate the capability to successfully operate a rover that can deploy scientific instruments.

Key engineering data will be acquired during Mars atmospheric entry to characterize the performance of the direct entry descent and landing system. This includes accelerometer measurements, airstream pressure and temperature measurements after parachute deployment, and temperature data acquired from sensors inserted in the aeroshell. The data will be returned in real time during descent and also recorded for later playback. Successful completion of this experiment will pave the way for cost-effective implementation of future Mars lander missions.

Additional engineering experiments to be performed by Mars Pathfinder include investigating the use of a highly integrated, high performance avionics package. Pathfinder also will use, for the first time, a commercially developed, multitasking computer operating system. Successful demonstration of this system will greatly simplify flight software development for future missions.

A key power system experiment to be performed on this mission is the assessment of solar array performance on the martian surface. Dust storms and other environmental phenomena may cause long term degradation, which can be investigated during the extended mission. Long term operations will also provide valuable information on the survivability of key spacecraft components in the severe thermal and dust environment found on the martian surface. This, in particular, is where the Lewis Research Center developed dust/solar array power output and dust abrasion experiments on the rover will contribute.

### **NASA LEWIS RESEARCH CENTER'S CONTRIBUTION TO THE MARS PATHFINDER MISSION**

The NASA Lewis Research Center of Cleveland, Ohio has a long history of involvement with missions to Mars. Lewis managed the launch of the Mariner, Viking and Mars Observer missions and designed the Earth-to-Orbit trajectories for the Atlas/Centaur and Titan/Centaur vehicles that maximized their payload capability to Mars transfer orbit.

NASA Lewis has been involved in the Mars Pathfinder mission nearly from the beginning and has contributed in three major areas: First, the results from an earlier Lewis developed "Mars Solar Energy Model" (Appelbaum, 1993), (Appelbaum, 1995) that models the solar flux at Mars surface provided confidence that sufficient solar energy is available at Mars surface to make solar powered spacecraft and vehicles practical, and then was subsequently used by JPL to design the lander and rover solar arrays. Second, the Lewis Space Power Facility and staff were utilized in the developmental testing of the Pathfinder airbag landing system. Thirdly, Lewis designed and provided three of the technology experiments that are on the rover as well as a static electricity discharge system.

### **Mars Solar Energy Model**

Solar energy has long been recognized as a potential power source for surface based operation on Mars. Detailed information on solar radiation characteristics on Mars are necessary for effective design of future photovoltaic systems. Recognizing this future need, Lewis Research Center sponsored work in the early 1990's to develop a model of the global, direct beam, and diffuse solar insolation on Mars that could be used in engineering design. This model has subsequently been used by NASA in the design of conceptual martian surface systems and by the Pathfinder project in the design of the lander and rover. The Mars Pathfinder findings will greatly enhance the accuracy and utility of the model.

### **Airbag Developmental Testing**

NASA Lewis Research Center's Plum Brook Station in Sandusky, Ohio hosted the JPL managed and ILC Dover (airbag contractor) developed testing of the airbag landing system in the Space Power Facility (SPF) over the period October 1994-May 1996. The SPF is the largest vacuum facility of its kind in the world and is utilized on a reimbursable basis by users from all over the world for testing of space systems. The vacuum chamber is 100 ft diameter and 122 ft high. For the Pathfinder tests a large inclined ramp with simulated Mars rocks bolted to it was placed in the chamber, the airbag system with dummy lander was suspended from the ceiling above the ramp and then slammed down on the ramp by a bungee cord system, under simulated Mars surface atmospheric pressure and temperature conditions (Fig. 4). This rigorous testing simulated the lander impacting the martian surface at 60 mph, with a wind drift of 30 degrees to the surface, and a deceleration of 60 times that of Earth's gravity. The pyramid shaped airbag system consists of 24 interconnected spheres and is 17 ft tall and 17 ft wide, and is fabricated from materials similar to those used in space suits. During this test program, the airbag design proceeded from an inadequate single layer of material construction to the final successful multiple layers of thinner material design.

### **Lewis Research Center Technology Experiments**

The future design of efficient exploration machinery for Mars depends on factors of the Mars surface environment that are presently not well understood. These include the typical solar insolation at the surface, the effects of the dust settling from the atmosphere on the operation of solar arrays, dust particle size and shape, the abrasiveness of the surface material, and electrostatic charging of moving machinery in the dry atmosphere. Consequently, a large portion of the Pathfinder mission is devoted to resolving these issues. Because of Lewis Research Center's expertise in space power systems, space mechanisms and tribology, and space environmental effects, JPL invited Lewis to participate in designing experiments to determine the effect of dust on solar array power output and surface material abrasion on metallic spacecraft parts. Later in the program the issue of rover electrostatic charging due to its movements in the dry environment (with possible damaging arcing) became an issue. Lewis was able to design and provide to JPL a static electricity discharge system that was incorporated on the rover to safely bleed off charge build-up. These items are further described below.

**Materials Adherence Experiments (MAE).** There are two materials adherence experiments on the rover intended to investigate

how dust settling from the martian atmosphere affects solar array power output (Landis, et al., 1996). These consist of two sensors. The first sensor contains a solar cell whose output current changes as dust settling from the atmosphere obscures the sunlight reaching its surface. The sensor consists of a moveable cover glass over a clean solar cell. As dust accumulates on the cover glass the cell output current degrades. Once a day at local martian noon, the cover glass is rotated such that the underlying clean cell is exposed. A series of such open and closed readings are then made of the output current with the cover glass on and off the cell. The output current comparisons are then an indication of the effect of the dust on cell performance. The cover glass movement is actuated by an innovative shape memory alloy actuator consisting of a nitinol (nickel/titanium alloy) wire which contracts as a function of increasing temperature. It is attached to a lever on the cover glass axle such that as an electrical current is passed through it, heating it to the threshold temperature, it contracts, much like a muscle, pulling the cover glass open.

The second materials adherence experiment is intended to measure the mass of dust per unit area falling on the array. This sensor consists of two electrically driven, vibrating quartz crystals stacked in a vertical configuration. The upper crystal is exposed to the environment and is coated with an adhesive to retain the dust that settles on it. This arrangement is known as a "Quartz Crystal Monitor" or "Quartz Crystal Microbalance" or QCM. The vibrational frequency changes with mass buildup. The difference between the frequency of the crystal accumulating dust and that of the underlying clean crystal provides a measure of the amount of dust accumulation. The QCM is capable of measuring very minute amounts of material and is often used to measure the amount of outgassing in aerospace and other systems. The experiment is performed in the same manner and same time each day as the solar cell experiment.

Both of these sensors reside in close proximity on a small "watchplate" 60 mm on a side which is located on the forward left corner of the rover array. The QCM control electronics, on a circuit board, reside within the rover body in a controlled temperature environment. The populated watchplate and circuit board have a combined mass of 65 g. In addition, the watchplate also contains another exposed solar cell whose open circuit voltage is measured and, when combined with the short circuit Lewis experiment cell, provides a measure of array power output performance. Together these two sets of measurements will provide excellent information on dust properties and deposition rates. Figure 5 shows the location of the Lewis experiments on the rover.

**Wheel Abrasion Experiment (WAE).** The wheel abrasion experiment will measure the abrasiveness of the martian regolith by measuring the wear of special metallic coatings on one of the rover wheels. The right center rover wheel was modified by Lewis with a 25 mm wide strip around the center of its circumference of black anodized (0.010 gage 7075-T6) aluminum overlaid with segments of the metals nickel, aluminum and platinum in varying thicknesses (200 to 1000 Å). As the metallic coatings are abraded away by the rover's traverses and wheel spins, the black underlying anodization becomes exposed. The change in spectral characteristics from reflected sunlight off that particular segment is detected by a small photocell mounted about a centimeter away on the wheel strut. Together, the wheel modification and photocell have a mass of only 12 g. Twice each martian day, all the other rover wheels are locked stationary while the WAE wheel is spun and allowed to dig into the

martian surface. Marked abrasion will indicate a surface composed of hard, possibly sharply edged grains, while lack of abrasion would suggest a somewhat softer surface. WAE results will be correlated with ground simulations to determine which terrestrial materials most closely resemble the wear patterns experienced by the WAE. The abrasiveness to aerospace materials likely to be used in Mars systems can then be inferred from this data. Also, this knowledge will enable a deeper understanding of erosion processes on Mars and the role they play in martian surface evolution.

A special vacuum chamber test rig was constructed for the development and calibration of this experiment. It simulates Mars conditions and contains a circular tray or turntable into which various "Mars dirt" simulants are placed. The tray is rotated under a test wheel with a magnetic brake to produce variable drag and simulate wheel slip. Wear data are then taken and will be compared with the actual Mars data.

**Rover Electrostatic Discharge System.** While the Pathfinder rover was being developed at JPL, tests and calculations done by the NASA Lewis Research Center indicated the very real possibility that, when moving over the martian surface, the rover would accumulate electrostatic charge (Kolecki, 1996). In a simulated test environment at Lewis, this charge was repeatedly shown to raise on-board electrical potentials above the suspected Paschen minimum of the martian atmosphere. The result of potentials of this magnitude could be a sustained Paschen discharge, with possible disruption of on-board electronics and production of electromagnetic noise. Methods of eliminating built-up charge were explored at the same time. Since significant mass could not be added to the rover, a lightweight, passive method was sought. One method appeared particularly attractive: the use of small, metal discharge points to "bleed" accumulated charge off the rover and into the martian atmosphere where wind-borne dust would carry it away.

When JPL was apprised of these results, Pathfinder engineers decided to implement the recommendation of adding discharge points to the rover. Subsequently, modifications were also made to rover on-board electronics. Six tungsten points were produced at Case Western Reserve University in Cleveland, Ohio. Four were mounted on the rover antenna base. While tests show that the points do not entirely eliminate accumulated charge, they certainly appear to work well enough to maintain on-board electrical potentials at acceptable levels. The discharge points developed for Pathfinder quite possibly represent the first charge-control hardware specifically designed to deal with system-environmental interactions on the surface of another world.

**Lewis Mission Operations and Data Analysis Program.** The Lewis experiments team consists of the engineers and scientists who conceived, designed and built the experiments and also the Principal Investigators who are operating the experiments during the course of the mission. They are responsible for interpreting the results of this publicly available data and making their results available to the scientific and aerospace engineering community.

## SUMMARY AND CONCLUSIONS

The NASA Lewis Research Center contributed in a variety of ways to the mission implementation and experiments program of the NASA/JPL Mars Pathfinder Mission. The Lewis experiment results, as well as contributing to new scientific knowledge of Mars, are being translated into useful engineering design information for the

follow-on Mars Exploration Program missions. Some of these missions will employ larger, more robust rovers that may range up to 50 km from the landing site. These missions will be greatly enhanced by the Pathfinder results.

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Figure 1.—Shortly before landing on the surface, a set of airbags is inflated to cushion the impact while the parachute and the tether are released and carried away by the rocket-assisted deceleration module.

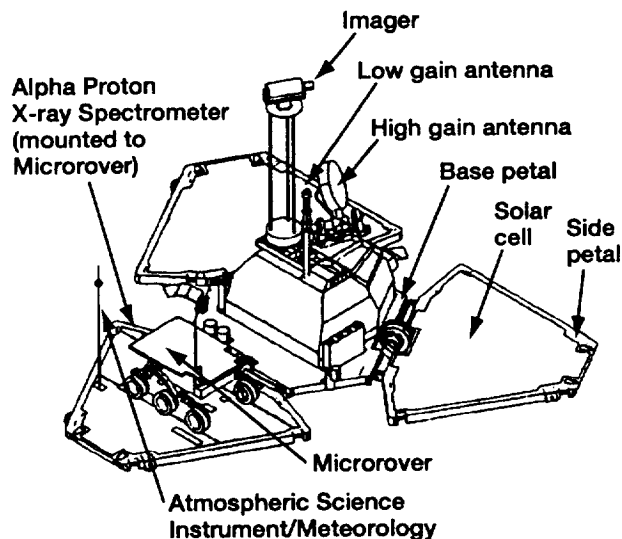


Figure 2.—Mars Pathfinder Lander and Micro rover.

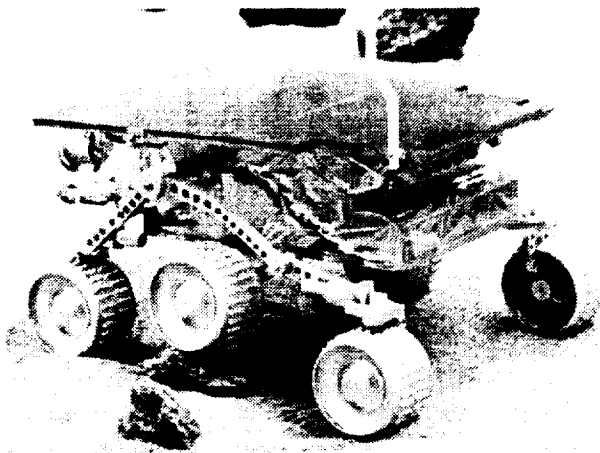


Figure 3.—The Pathfinder rover, Sojourner, developed at the Jet Propulsion Laboratory, will be the first autonomous vehicle to explore the surface of another planet.

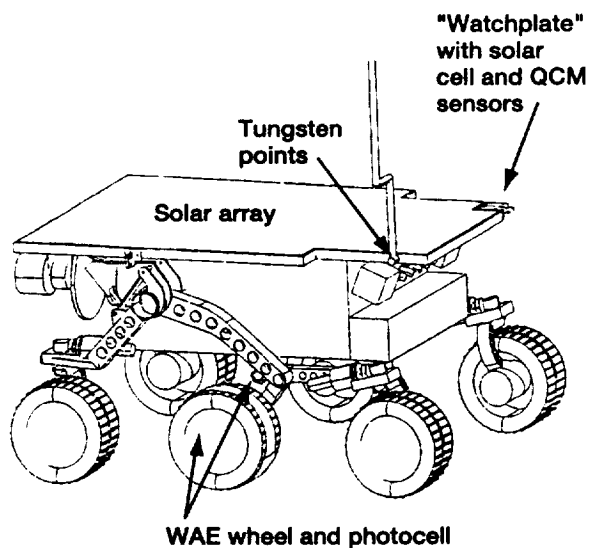


Figure 4.—Microrover "Sojourner" showing the location of the Lewis Research Center Experiments.



Figure 5.—The Mars Pathfinder air bag landing gear system performed impressively in a series of rigorous tests in Plum Brook's Space Power Facility. The air bag system is pictured being readied for a drop test onto a simulated Martian terrain.



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