Final Technical Report

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for

Mars Pathfinder Wheel Abrasion Experiment Ground Test

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The NASA Mars Pathfinder Mission

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Sidebar

The Mars Surveyor '98 is the next generation of spacecraft that will be sent to Mars. Consisting of an orbiter (to be launched this December) and a lander (to be launched in January 1999), the mission has a science theme of "Volatiles and Climate History." The Mars 98 orbiter will provide detailed information about the surface and climate of Mars. The Mars 98 lander will land near the southern polar cap on Mars. The lander is equipped with a stereo camera, a robotic arm and instruments to measure the martian soil composition. Two small microprobes are also piggybacking on the lander, which will separate from the lander during entry into the martian atmosphere and punch into the soil to determine if water ice is present. The microprobes will also measure soil temperature and monitor local martian weather.

Abstract

The National Aeronautics and Space Administration (NASA) sent a mission to the martian surface, called Mars Pathfinder. The mission payload consisted of a lander and a rover. The primary purpose of the mission was demonstrating a novel entry, descent, and landing method that included a heat shield, a parachute, rockets, and a cocoon of giant air bags. Once on the surface, the spacecraft returned temperature measurements near the Martian surface, atmosphere pressure, wind speed measurements, and images from the lander and rover. The rover obtained 16 elemental measurements of rocks and soils, performed soil-mechanics, atmospheric sedimentation measurements, and soil abrasiveness measurements.

Introduction

On July 4, 1997 America returned to the red planet after more than 20 years with the landing of Mars Pathfinder. Before losing contact with the spacecraft on September 27, 1997, the spacecraft returned pictures of martian sunrises, a rocky terrain, and the Sojourner rover crawling from rock to rock.

Mars Pathfinder was the second launch of the Discovery program (the first was Mars Global Surveyor (MGS) on November 7, 1996) of low cost planetary missions. One of the mission objectives was to demonstrate a simple, low-cost system for placing a science payload on the surface of Mars at one-tenth the Viking mission cost. The

Pathfinder spacecraft used an innovative method of directly entering the martian atmosphere. It was slowed by a heat shield, parachute, and then rockets. The spacecraft descended to the surface of Mars and landed using a cocoon of airbags to cushion the impact.

Over the course of the spacecraft's lifetime, the Mars Pathfinder returned about 2.3 gigabits of data, which included 16,500 images from the lander camera and 550 images from the rover camera, and about 8.5 million temperature, pressure, and wind measurements. All the science objectives had been fulfilled when the mission was declared over on November 4, 1997. One remaining objective was to complete a high resolution 360°-image of the landing site called the "Super Pan," of which 83 percent was received.

Sojourner explored about 250 square meters of the martian surface traveling about 100 meters in a total of 230 commanded maneuvers, performed 16 in-situ elemental analyses of rocks and soil with the alpha proton x-ray spectrometer, and carried out many soil mechanics and technology experiments. The rover returned data and images for 83 martian days, much longer than the projected thirty day lifetime for the lander and seven day minimum for the rover. A martian day is about 24.6 Earth hours.

The most important achievement of Pathfinder may not have been the data returned, but the new philosophy that the spacecraft was designed under. Pathfinder was National Aeronautics and Space Administration's (NASA's) first big test of its "better, faster, cheaper" mandate. NASA engineers had to come up with a new way to deliver a spacecraft to the martian surface much cheaper than and more quickly than the Viking program. Compared to the $1 billion price of one Viking mission (about $3 billion in current dollars), the cost of Mars Pathfinder was $280 million including launch vehicle and mission operations. One way that costs were cut was by using solar cells for lander and rover power instead of the more expensive---and politically less appealing---Radioisotope Thermoelectric Generators (RTGs) of the Viking missions.

Launch and Injection

The Pathfinder was mated to the Delta II launch vehicle during its assembly as shown in Figure 1. The Pathfinder spacecraft was launched on December 4, 1996 on a Delta II rocket from Kennedy Space Center. Once in Earth orbit, a solid-fuel rocket gave the spacecraft the final boost giving it the correct change in velocity to put the spacecraft in orbit around the sun. After the solid-fuel rocket was spent, it was jettisoned. The Deep Space Network (DSN) initiated spacecraft acquisition with the spacecraft using a 34 meter dish at Goldstone, California. As soon as acquisition had occurred, the spacecraft broadcast telemetry at 40 bits per second. This telemetry is a combination of real-time engineering data and stored data from launch, separation, and Earth/Sun acquisition. During the seven month cruise, the DSN also located the spacecraft and received telemetry so the four trajectory correction maneuvers (TCMs) could be made. TCMs are velocity changes to reduce navigation guidance errors. The fifth TCM was unnecessary since the spacecraft was on target to touchdown in the selected landing site.

Entry, Descent, and Landing

The spacecraft entered the atmosphere directly (without orbiting Mars like the Viking I and II landers) [1]. The cruise stage of the spacecraft, consisting of the solar cells and the hydrazine thrusters, separated 35 minutes before the spacecraft landed. Figure 2 illustrates the sequence of events in the entry, descent, and landing sequence. Pathfinder used a Viking-derived heat shield to decelerate the spacecraft from 7470 m/s to 370 m/s, using friction with the martian atmosphere, and then released a parachute. Twenty seconds after the parachute deployed, the heat shield separated. Using radar to sense the height of the spacecraft, the airbags surrounding the lander were commanded to inflate at 355 m above the surface. At 98 m above the surface the rockets ignited slowing the spacecraft to about zero vertical speed. At about 21.5 m above the surface, the tether connecting the probe to the retro-rockets was cut, letting the airbag-encased lander fall to the surface and bounce 16 times before rolling to a stop. The airbags were deflated 20 minutes after landing, then retracted, and finally the petals were opened. This entry, descent and landing (EDL) sequence marked the first time airbags were used for landing.

The novel landing system had some advantages over the conventional method of a soft rocket-assisted touchdown. The airbag landing method reduced the rocket exhaust contamination of the surface near the lander, since the spacecraft rolled to a stop far from the separation between it and the rockets. That surface would later be analyzed by the alpha proton X-ray spectrometer. Another advantage of the airbag landing method is that the spacecraft would not likely get wedged between rocks, preventing the petals of the lander from opening, since the diameter of the inflated airbags is larger than the lander with the petals opened.

After the airbags were deflated, the lander came to rest on its base. The lander could have touched down on any of the four faces of the tetrahedral-shaped lander which would have required that the lander be righted by means of the petal movement. Figure 3 is a schematic of the lander and the rover and the location of some scientific instruments. Because the lander did not have to right itself, a radio signal from the low-gain antenna was received only 97 minutes after landing on sol 1, the first martian "day" on Mars.

Commands were sent from Earth to unlatch the Imager for Mars Pathfinder (IMP) and the high-gain antenna on the lander. Stereo images from the camera were used to determine if it was safe to deploy the rover ramps. On sol 2, the small, 10.5 kilogram rover was deployed from the lander. The atmospheric structure investigation/meteorology (ASI/MET) mast was also deployed, which consists of a suite of sensors to measure wind speed and direction, and temperature of the atmosphere at three points above the surface.

Surface Operations

Some of the lander cameras images were used to plan the destinations for the rover. Controllers on Earth sent "waypoints", or destinations for the semiautonomous rover to go to, and then the rover found the best way to reach these waypoints itself. The rover used two binocular cameras and a laser ranging device to search the terrain for obstacles. The rover onboard computer processed this navigation data as well as performed other computing and control functions. The round trip signal delay from Earth to Mars was at least 10 minutes—too long for rover controllers to inch the rover forward and search for the terrain hazards themselves. The semi-autonomous capability of the rover allowed the rover to maneuver without being constantly under driver command.

Semi-autonomous capability is important for future long-range missions, including the Mars sample collection.

The rover could not communicate directly with Earth but instead communicated with Earth by means of a UHF radio link with the lander. High and low gain antennas on the lander, in turn, sent data back to Earth and received commands for the lander and rover to perform.

Imaging

Pictures from the IMP revealed a rocky plain about 16 percent covered by rocks. Many characteristics of the landing site are consistent with being deposited by a catastrophic flood. Remote-sensing from Viking orbiters showed similarity to the Channeled Scabland in eastern and central Washington state. The rocks and pebbles at the landing site appears to have been swept down and deposited by floods in the Ares and Tiu regions near the Pathfinder landing site [1]. The number of impact craters in the region indicates it formed at an intermediate time in Mars history: between 1.8 and 3.5 billion years ago.

Rocks from a few centimeters in size to 7 meters are seen in all directions from the lander. Angular rocks are tilted in a downstream direction from the flood. Large rocks are flat-topped which is consistent with deposition by a flood [2]. Also the undulations of the terrain indicate the direction of flood waters. Figure 4 shows the rover on a rock tilted in the direction that the flood waters are thought to have flowed.

Overall three types of rocks and four classes of soil were found at the landing site. Most rocks are dark gray and are covered with yellow-brown dust. This dust appears to be the same as in the atmosphere. Dust that settled from the atmosphere is also deposited behind rocks in tails by the wind. Dirt covering the lower 5 centimeters of some rocks suggests they have been exhumed by the wind. Some rocks appear to have been fluted by wind-driven sand-sized particles.

Rover images showed sockets and pebbles in some rocks, suggesting that these rocks are conglomerates. Conglomerates are usually formed in running water, which rounds the pebbles in the conglomerate. Running water is also necessary to deposit these pebbles in a sand or clay matrix. This evidence suggests a warmer and wetter planet in the past in which liquid water flowed on the surface and a thicker atmosphere maintained a higher surface temperature.

Atmospheric Conditions

The ASI/MET sensors measured air pressure, temperature, and wind speed. The winds were light and variable compared to the those encountered by the Viking landers. The winds blew steadily from the south during the martian nights, but during the day they rotated in a clockwise direction from south to west to north to east. Whirlwinds or dust devils were detected repeatedly from mid-morning through the late afternoons. Whirlwinds showed a marked temperature and pressure change as they passed over the lander. At least one may have contained dust suggesting that these gusts are a mechanism for mixing dust in the atmosphere.

Dust suspended in the atmosphere was confirmed as the dominant absorber of sunlight. Figure 5 shows the scattering of sunlight by suspended dust. The atmospheric opacity is about 0.5. Opacity is a measure of how much light is blocked by the atmosphere. The slightly higher opacity at night and early in the morning may be due to frozen water vapor clouds as shown in Fig. 6. The sky has a pale pink color, similar to what was seen by the Viking landers. Suspended dust of about 1 micrometer in size and the amount of water vapor in the atmosphere are consistent with measurements made by Viking. The amount of water vapor in the atmosphere would only result in a layer 0.01 mm thick if all of it rained out.

Pathfinder measured regular pressure fluctuations twice a day, suggesting that some dust was being mixed in the lower atmosphere. Atmospheric pressure underwent a daily substantial variation of 0.2 to 0.3 mbar, which was primarily associated with the large temperature changes in thin martian atmosphere. The mean martian atmospheric pressure is about 6.7 mbar.

Atmospheric temperature was measured by four thermocouples: one designed to measure temperature during parachute descent and three designed to measure surface temperatures at 25, 50, and 100 cm above the base of the mast [3]. Pathfinder arrived in the late northern martian summer. The martian surface temperatures followed a regular daily cycle, with a maximum of -9° C in the day and a minimum of -76° C at night. Temperatures can plunge 22 C degrees in a matter of minutes. Since the atmosphere is so thin, the atmosphere warms near the surface and convects upward during certain times of the day.

Alpha Proton X-ray Spectrometer

The APXS is an instrument on the rover which is able to determine the elemental composition of rocks and surface material. The APXS uses a radioactive source which produces alpha-particle radiation and then looks at the backscattered energy spectrum.

Before the Pathfinder mission the knowledge of the kinds of rocks present on Mars was based on Viking results, and on the martian meteorites found on Earth, which are all mafic igneous rocks rich in magnesium and iron and low in silica. Chemical analyses of 8 rocks, along with the spectral images of rock colors (performed by rotating filters in front of the lander imager cameras), confirmed that these rocks had different compositions from the martian meteorites found on Earth [4].

The rocks that were analyzed by the rover's APXS, as shown in Fig. 7, were of andesitic (high in silicon) origin. The high silica or quartz content of some rocks suggest that they were formed as the crust of Mars was being recycled, or cooled and heated up, by the underlying mantle. Analyses of rocks with lower silica content appear to be rich in sulfur, implying that they are covered with dust or weathered. Rover images show that some rocks appear to have small air sacks or cavities, which would indicate that they may be volcanic. The soil chemistry of Ares Vallis appears to be similar that of the Viking I and II landing sites, which suggests global dust mixing. Soils, however, cannot have formed from the analyzed rocks at the landing site because their compositions are different. Soils are lower in silicon than the rocks and higher in iron, sulfur, and magnesium.

Magnetic Properties of Airborne Dust

Magnetic dust in the martian atmosphere gradually covered most of the magnetic targets on the lander. The magnetic targets have different magnetic field strengths to attract different magnetic minerals in the dust. The dust covering the magnetic targets is bright red with a magnetic strength similar to composite particles, meaning that they are composed of several materials. A small amount of the mineral maghemite in the dust has been deposited as a stain or cement. This method of deposition is interpreted to mean that that the iron was dissolved out of crustal materials in water, suggesting a once active hydrologic cycle of Mars, and the maghemite may be a freeze-dried precipitate [5].

Doppler and Ranging Experiments

The radio communications with Pathfinder were used to measure the distance of Pathfinder to the Earth, and to determine the rotation rate of Mars. Daily radio Doppler tracking and less frequent two-way radio ranging during communications sessions with the spacecraft determined the position of the lander in inertial space and the direction of Mars' rotational axis. These results combined with the Viking results 20 years ago improve the measurement of the precession rate by a factor of three. Precession is the direction of the tilt of the axis of the planet. The difference between the two positional measurements yields the precession rate. This rate is a function of the distribution of mass within the planet, called the moment of inertia. From Pathfinder's data Mars must have a dense core surrounded by a lighter mantle and the radius of Mars' metallic core must be between 1300 kilometers and 2400 kilometers [6].

In addition to the precession rate, Pathfinder detected a seasonal change in the rotation rate of Mars about its spin axis which is thought to have varied because of mass exchange between the polar caps and the atmosphere. During the winter, part of the atmosphere condenses at the poles. The waxing and waning of the martian polar ice caps also results in seasonal changes of air pressure at the Pathfinder and Viking landing sites. At the Pathfinder landing site the yearly pressure cycle reached a minimum at sol 20, meaning that the southern polar cap reached its maximum mass.

Pathfinder and Future Missions

The Pathfinder mission demonstrated a low-cost system for placing science and technology payloads on the martian surface. The lessons learned and the science returned from Pathfinder will be applied to future missions. For example, the atmospheric pressure data will be used to design future reentry heat shields and the elemental composition of rocks and dust at the Pathfinder site will provide calibration data for the Mars Global Surveyor thermal emission spectrometer.

NASA Lewis Research Center designed and built technology experiments on the rover. One evaluated the abrasiveness of martian dust [7], and another measured the sedimentation rate of atmospheric dust [8]. Lewis' Plum Brook Station also tested the Pathfinder airbag landing system as shown in Fig. 8. A later article in LE will discuss the design, and the flight and ground results of the experiment which evaluated the abrasiveness of martian dust, called the wheel abrasion experiment.

Pathfinder was the first of nine Mars missions to be launched in the 1996-2005 time frame which comprise the long-term Mars exploration initiative. The missions will typically consist of orbiter and lander pairs launched at every 26 month launch opportunity. The next orbiter-lander pair is scheduled to launch in December 1998 and January 1999, called Mars Surveyor 98 which is described in the italicized sidebar. The Mars Surveyor 2001 Lander and Rover mission will feature a backup of Sojourner rover. There are also tests to produce rocket propellant, measure radiation, and also evaluate dust accumulation and removal technology. The Mars Surveyor 2001 orbiter will characterize the mineralogy and chemistry of the surface. The Mars Surveyor 2003 Lander and Rover will gather samples for possible later return. The Mars Surveyor 2003 Orbiter will provide communications for later missions. The Sample Return Mission will feature a landing on Mars, and the collection of samples from previous missions, and a return to Earth by 2008.

Captions of Figures

Fig. 1---Pathfinder mated to Delta II launch vehicle. The Pathfinder lander and rover are enclosed by the heat shield and backshell, called the aeroshell, at the top of the structure. The graphite-epoxy aeroshell provides thermal protection and can withstand the forces from a 16-g deceleration during atmospheric entry. The cruise stage is the white ring beneath the backshell and includes the hydrazine tanks covered in gold foil. Solar cells on the cruise stage provide the spacecraft power during cruise.

Fig. 2---A series of entry, descent, and landing events was executed, resulting in a successful landing on the martian surface.

Fig. 3---Mars Pathfinder lander. The three petals are covered with solar cells to power the lander. The flat surface on top of the rover is covered with solar cells to power the rover. Both the lander and rover have batteries to operate during low light.

Fig. 4---The rover wheel with the shiny surface forward is on top of the rock Wedge on sol 47. Wedge is tilted in the direction flood waters are thought to have flowed.

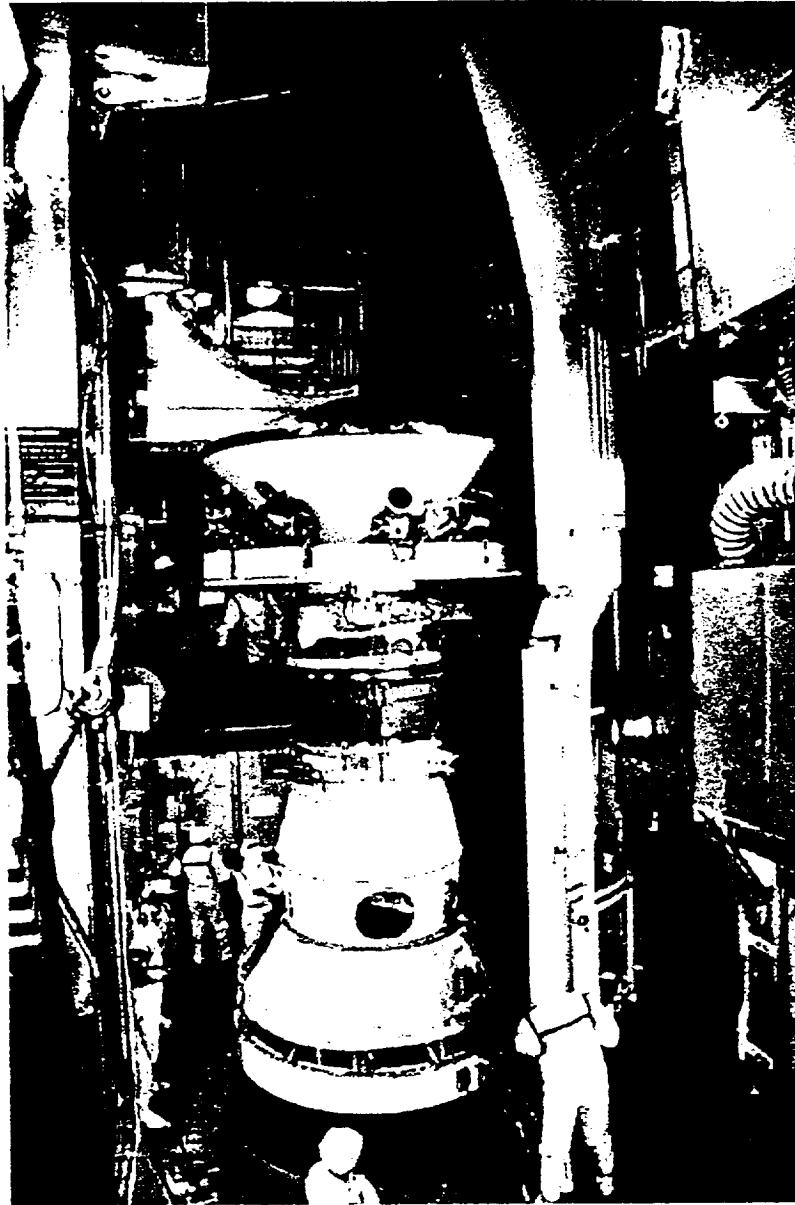Fig. 5---Lander image of sunset showing fan-shaped scattering of light from suspended dust.

Fig. 6---True color image of the eastern sky on sol 39. The bright streaks are probably water ice clouds, which have formed during the night.

Fig. 7---Image of Sojouner rover conducting elemental analysis of the rock Yogi with alpha proton x-ray spectrometer (APXS).

Fig. 8---Testing of airbags at NASA's Lewis Plum Brook Station. The airbags were dropped in this facility in order to simulate martian atmospheric pressure (0.7 percent of Earth's).

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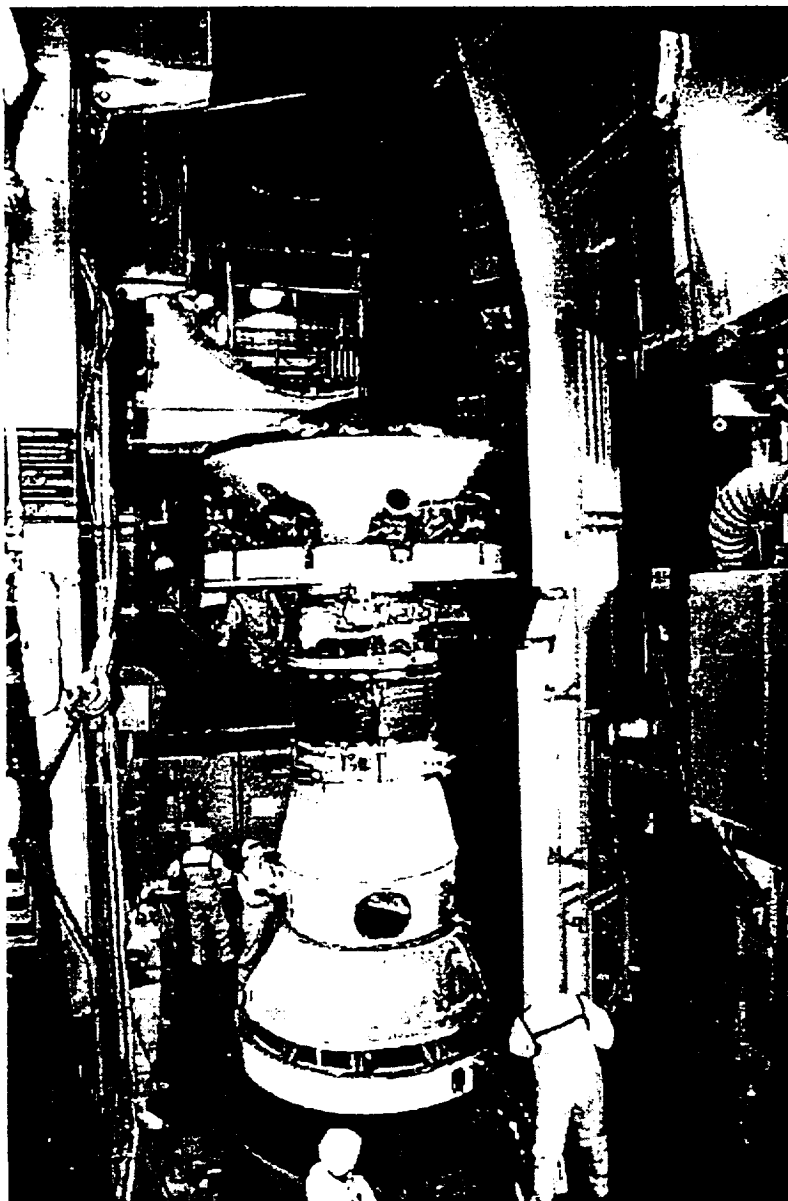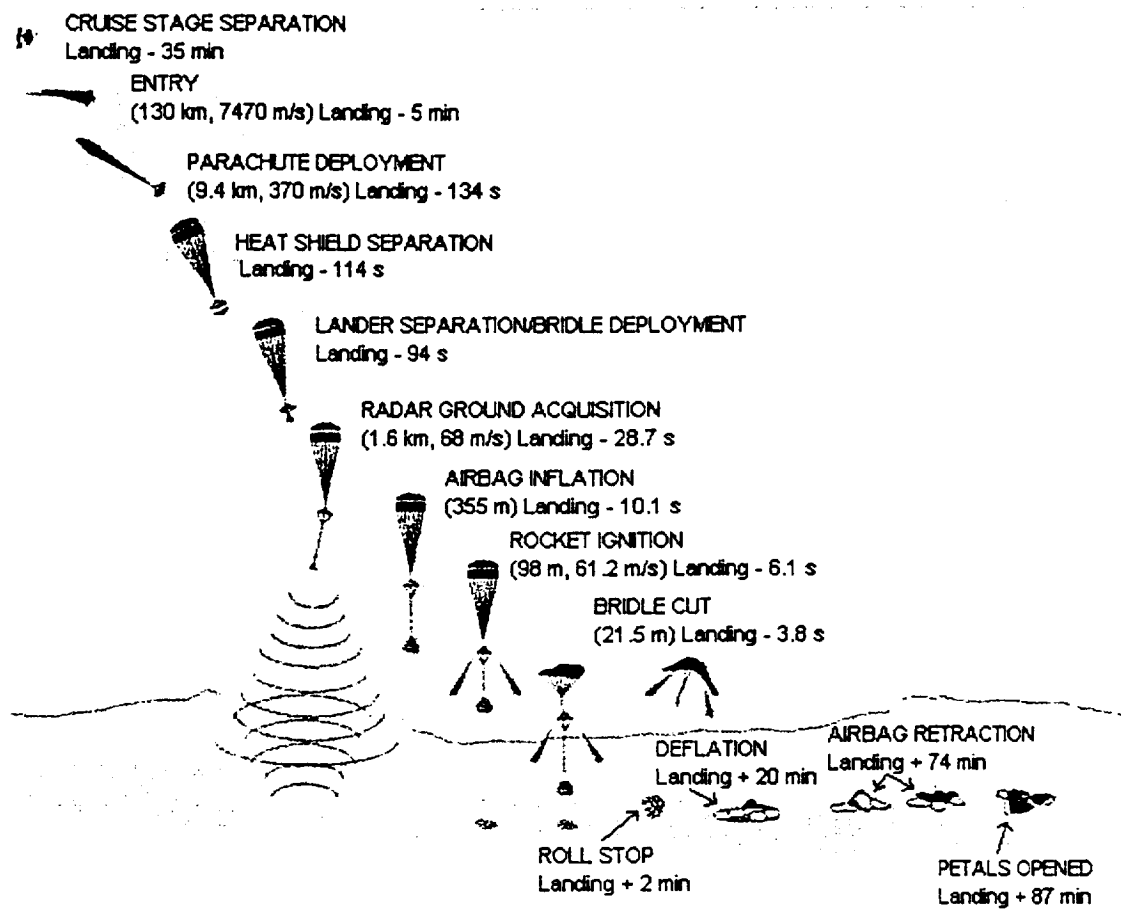
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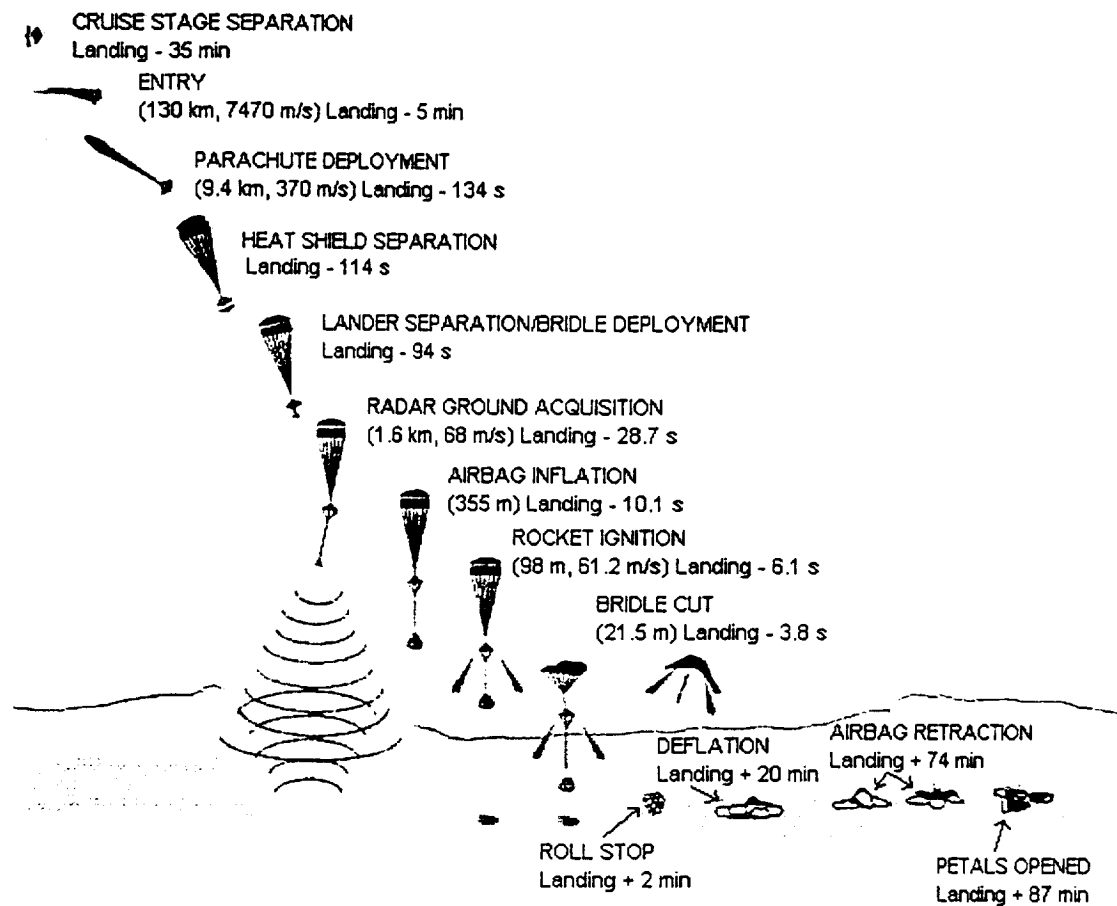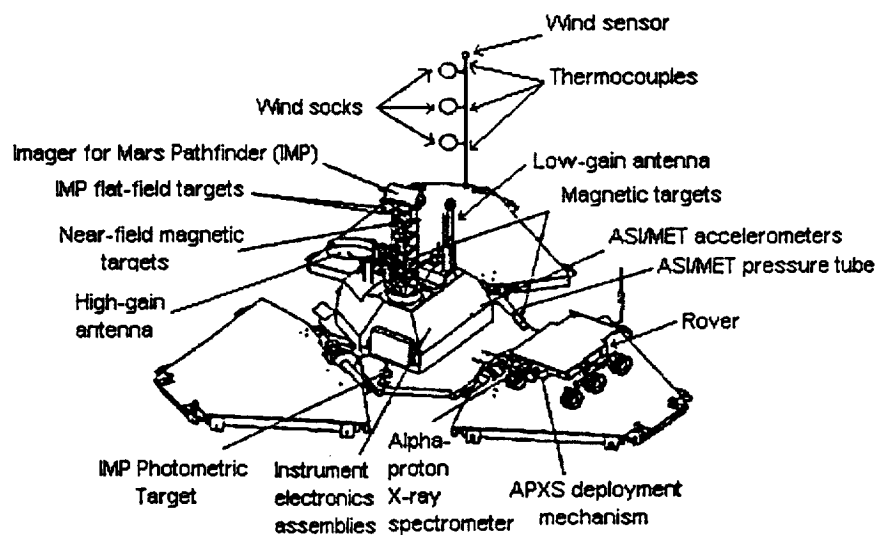
CRUISE STAGE SEPARATION
Landing - 35 min

ENTRY
(130 km, 7470 m/s) Landing - 5 min

PARACHUTE DEPLOYMENT
(9.4 km, 370 m/s) Landing - 134 s

HEAT SHIELD SEPARATION
Landing - 114 s

LANDER SEPARATION/BRIDLE DEPLOYMENT
Landing - 94 s

RADAR GROUND ACQUISITION
(1.6 km, 68 m/s) Landing - 28.7 s

AIRBAG INFLATION
(355 m) Landing - 10.1 s

ROCKET IGNITION
(98 m, 61.2 m/s) Landing - 6.1 s

BRIDLE CUT
(21.5 m) Landing - 3.8 s

DEFLATION
Landing + 20 min

AIRBAG RETRACTION
Landing + 74 min

ROLL STOP
Landing + 2 min

PETALS OPENED
Landing + 87 min

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PETALS OPENED
Landing + 87 min

Fig. 2---A series of entry, descent, and landing events was executed, resulting in a successful landing on the martian surface.

Wind sensor

Thermocouples

Wind socks

Imager for Mars Pathfinder (IMP)

IMP flat-field targets

Low-gain antenna

Magnetic targets

Near-field magnetic targets

ASI/MET accelerometers

ASI/MET pressure tube

High-gain antenna

Rover

IMP Photometric Target

Instrument electronics assemblies

Alpha-proton X-ray spectrometer

APXS deployment mechanism

Fig. 3---Mars Pathfinder lander. The three petals are covered with solar cells to power the lander. The flat surface on top of the rover is covered with solar cells to power the rover. Both the lander and rover have batteries to operate during low light.
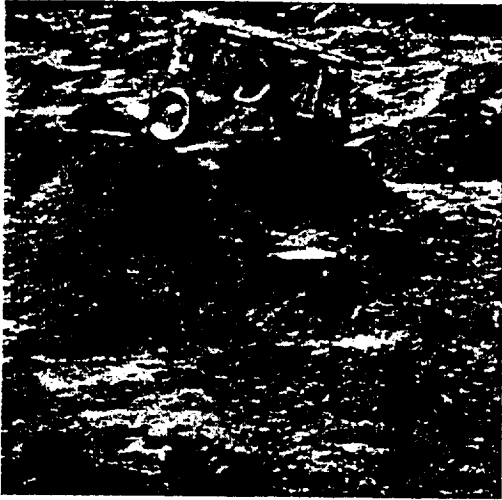

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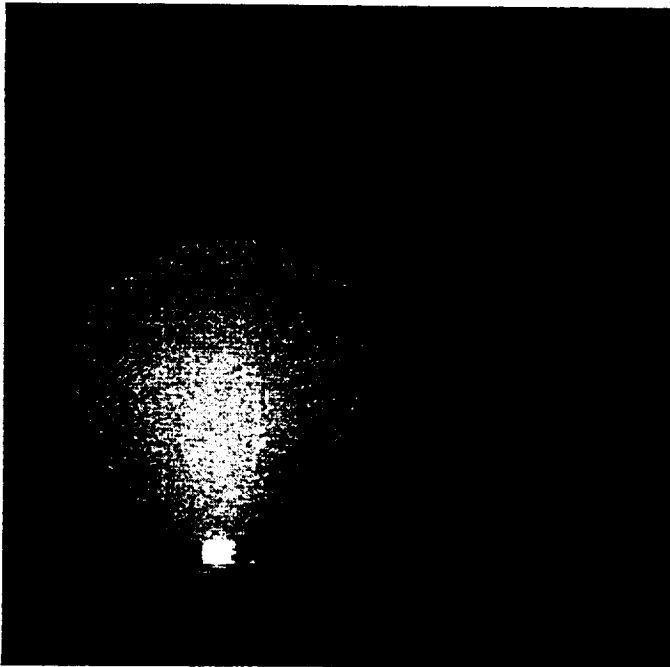

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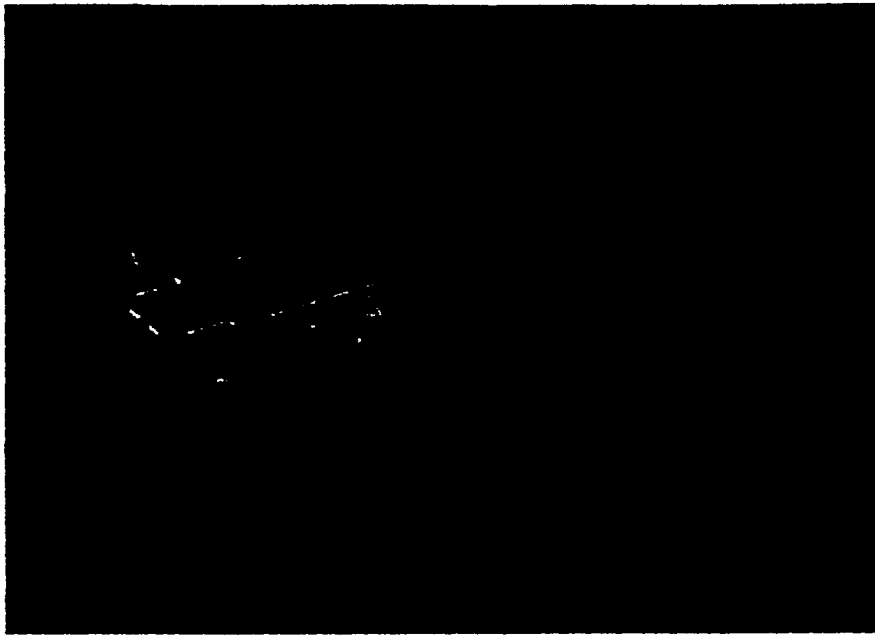
figure6summary.bmp (256x285x16M bmp)

figure7summary.bmp (446x314x16M bmp)

Fig. 8---Testing of airbags at NASA's Lewis Plum Brook Station. The airbags were dropped in this facility in order to simulate martian atmospheric pressure (0.7 percent of Earth's).

Mars Pathfinder Wheel Abrasion Experiment----Ground and Flight Results

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ABSTRACT

Mars Pathfinder conducted scientific and technology experiments with a rover and a lander. One of the technology experiments carried by the rover was a tribological experiment, called the wheel abrasion experiment, designed to evaluate the abrasiveness of martian surface material. The experiment was carried on one of the wheels of the rover, Sojourner. Wear was detected by a photodetector through the reduction of reflectance of three types of metal films (Al, Pt, and Ni) on a black anodized substrate attached to the wheel. The Pathfinder mission showed that significant wear occurred on the metal wheel strips, with the most wear on the thinnest aluminum samples, and the least on the thickest nickel and platinum samples. The depth of dig during a wheel abrasion experiment showed that the dust is, in some places, very loose, and in other places tightly packed. Laboratory tests showed that the surface simulants used for wear testing in the ground tests adhered to the wheel and electrostatic charging of the wheel occurred.

INTRODUCTION

The properties of martian dust are of interest to spacecraft designers. The low pressure but high speed martian winds can transport large amounts of dust during global dust storms [1] which are visible, for example, with the Hubble Space Telescope. The Viking missions and the Pathfinder mission also showed that the pinkish tint of the martian atmosphere is a result of suspended dust. Further evidence of dust transport on Mars is that the surface material from Viking Lander 1 and 2 sites, although 1000 km apart, is virtually identical in elemental composition [2]. At the Pathfinder landing site, the measured compositions of the rocks was different from the dust, suggesting that the dust was not formed from the analyzed rocks but rather was transported there.

One experiment on the Mars Pathfinder determined how much dust is deposited on solar arrays from atmospheric sedimentation [3]. The purpose of the Wheel Abrasion Experiment (WAE), however, was to learn about different aspects of the dust. For example, is the dust fine enough to infiltrate mechanisms? Is the dust so abrasive that mechanisms could be at risk? Can the moving rover build up an electrostatic charge? Can electrostatic charging of a moving rover play a role in attracting dust to surfaces? In

order to help answer these question about the martian dust, the WAE was included on the Mars Pathfinder Sojourner rover [4].

The Mars Pathfinder, the first mission to land on Mars since Viking 21 years ago, was part of the National Aeronautics and Space Administration (NASA) Discovery Program. The Discovery Program is a series of planetary exploration missions to perform science investigations in shorter time and lower cost than previous missions. The overall goals of the Pathfinder mission were to demonstrate a simple, low-cost system for placing science payloads on the surface of Mars at an order of magnitude lower cost than Viking and to demonstrate NASA's commitment to low-cost planetary exploration by completing the mission at a total cost of $280 million, including launch vehicles and operations, and to demonstrate the usefulness of a microrover on the surface of Mars.

DESIGN PHILOSOPHY

A wheel wear experiment was first proposed as a possible Mars Pathfinder rover technology experiment in late 1992. The ground rules established early in the Pathfinder program were that the rover technology experiments should be small and lightweight, consume little spacecraft power, require as little telemetry as possible, and not be necessary for the operation of the rover itself, so that failures of the technology experiments would not lead to loss of the science mission. More specific requirements include being able to withstand a 60 g landing load, to withstand the launch vibrational environment, and to operate to -50 °C. In early 1993, the WAE was deemed satisfactory from the standpoints of telemetry requirements, vehicle unobtrusiveness, and the go-ahead was received for further development [5].

The initial concept of the wheel wear experiment was to measure how abrasive the martian dust is by measuring wheel wear as the Sojourner wheel traverses the landing site. Initial rough calculations based on analogies with Earth-bound tire wear showed that in a few hundred meters of travel, hundreds of Angstroms of material wear should occur. This small amount of wear, of course, would have no measurable effect on the operations or appearance of the wheel themselves. An experiment would be necessary to allow measurements to be made. Special wear strips would be necessary as well as a sensor to detect wear.

Thin strips of fluorescent paint were initially thought to be the best material of which to measure wear. A photodetector would be used measure the loss of thin films of the fluorescing paint. Since solar UV impinges practically unimpeded onto the martian surface, the fluorescent glow would stand out against the background. Fluorescent paints, however, were ruled out early in the program for several reasons—even good fluorescence would not add significantly to the reflected sunlight and depositing very thin, but well calibrated thicknesses of paint would be difficult, and the wear rates of the paints may not be similar to the wear rates of metals, which would be primarily used in technology applications on the martian surface. It was therefore decided that very thin (=<1000 Å) layers of pure metals would be deposited on a hard black substrate. The changes in the reflected martian sunlight would be used to detect wear on the metal strips by a photocell. Since the reflectivity of pure metals is much higher than the black

substrate, the wear of the metal can be detected by a decrease in reflected light. The right middle wheel of Sojourner's six wheels was chosen for the WAE.

Typically wear is measured in the laboratory by conducting surface profilometry of the test specimen before and after the wear test, or by photographing the wear scar and then calculating wear, or by measuring weight loss. Since these methods were not feasible on Mars because of the high mass of equipment required, another way had to be used. The sensor, to detect changes in reflectance, is photovoltaic. A photovoltaic detector is very linear over a wide range in brightness, is passive, provides an analog output compatible with the Sojourner A/D converters, is easy to calibrate, and is highly reliable. Also, the wispy clouds on Mars were unlikely to change the light input significantly.

After considering various telescopic collimators and honeycomb collimators, we chose a three cell detector mounted on the WAE wheel strut, with each cell masked by geometrical optics so that all three solar cells view only one metallic wear coupon at the same time. The rover orientation and time of day were selected so that sunlight would be approximately specularly reflected from the observed wheel strip into the detector, where the electrical signal would be generated and read out by A/D converters on the rover.

FLIGHT HARDWARE

The flight hardware of the wheel abrasion experiment consisted of the photodetector and the wear strips. The design of each of these components is discussed in the following paragraphs.

A series of seven metals was examined for suitability for the metal coatings on the wear strips [4]. The seven candidate metals were Ag, Al, Au, Cu, Ni, Pt, and W which were chosen to represent a cross section of properties (melting point, hardness) and applications (electronic and structural).. These metals were deposited by e-beam or resistive evaporation on black anodized coupons for reflectance measurements. Metal film thickness varied from 0.1 to 1.0 micrometer. Reflectance measurements were made on a spectrophotometer with an integrating sphere to capture all reflected light. Reflectance of the strips was measured from 400-1000 nm.

After reflectance measurements were made, an adhesion test of the metal films was conducted. This was done to assure sticking of the metal film to the substrate and to preclude apparent wear of the metal films by delamination. A strip of commercial adhesive tape was attached to coupons of each of the candidate metals and removed. The results of each test were graded by visual inspection. Peeling of under 10 percent was considered excellent; peeling of 10 to 25 percent was considered good; peeling of 25 to 50 percent was considered fair, and any peeling greater than 50 percent was considered unacceptable. Based on this criteria, the adhesion of the seven metal films ranged from poor to excellent.

A gallium arsenide on germanium (GaAs/Ge) photodetector was chosen for the WAE. Based on the optical response of the detector (band edge at 860 nm), an average reflectance was determined for each metal in the range of 400-800 nm from the measured range of 400-1000 nm. Four of the seven metals were eliminated because of poor adhesion to substrate, tarnishing, low reflectance, or light absorption. The three metals

chosen each had a relatively flat reflectance value throughout the visible and near-infrared spectrum, 400-800 nm. Aluminum was chosen for its high reflectivity, 0.71 in the 400-800 nm range and its softness, and nickel and platinum because of good reflectivity and adhesion. The hardnesses of the metals chosen ranged from soft to hard to yield different wear rates. On the Brinell hardness scale, aluminum is about 16, platinum about 64, and nickel about 100 [6].

The flight hardware was built using three strips of 7075-T6 aluminum alloy that were black anodized, resulting in an alumina surface impregnated with black dye. The strips were 25 mm x 120 mm x 0.25 mm. Each metal was resistive-evaporation-deposited in thicknesses of 200, 300, 450, 700, and 1000 Å on a single strip on top of the now black metal strips. One strip was made for each deposited metal: Al, Pt, and Ni. The pattern of metal (M) and bare spots (B) of each strip is: BMBMMBMM. The unique pattern allowed each coupon to be identified by the photodetector output. Each metal abrasion sample is adjacent to a black reference coupon, and the thinnest sample of each metal is between two black reference samples. The strips are shown attached to the wheel of the rover in Fig. 1.

The final photodetector design included three small GaAs/Ge solar cells wired in parallel and connected to a load resistor [7]. A load resistor was included so the output voltage is linear with incident light intensity. The load resistor was sized so that the photodetector would not saturate in martian sunlight. Geometrical optics limited the field of view to slightly smaller than one abrasion sample when viewed at an angle of incidence of 30° and a separation distance of 19.2 mm (center of sample to front of detector). The three apertures limited the field of view. Optical baffle plates between each of the three photocells isolated them.

The photodetector was attached to the bogie which supports the center-right wheel (Fig. 2). The photodetector maintained its angular position with respect to the wear strips on the wheel during a wheel abrasion experiment. As the wheel turned in the martian soil, the metal films were worn away exposing the black anodization. The photodetector monitored the reflectance off the samples. Reduced reflectance ideally corresponds to metal film wear.

A WAE calibration using prototype wheel and photodetector is shown in Fig. 3. This calibration was performed by using flight spare wheel and wear strips hardware. The light source of the calibration is a photographic test lamp which produced 25 percent Mars light intensity on the wear strips. Several features are notable in the calibration data. The black samples do not produce a zero output from the photodetector. The black anodized samples has a low reflectance (<5 percent) up to 700 nm, where it begins to reflect. At the band edge of the GaAs photocell (870 nm), the reflectance has increased to >40 percent. This reflectance accounts for the non-zero reference value.

FLIGHT WAE PROCEDURE

To perform a WAE on Mars, the Wheel Abrasion Command was sent to the rover from Earth. In a WAE all wheels were locked except the wheel abrasion wheel which was spun in the backward direction, digging into the martian surface, while photodetector data was acquired. The WAEs were typically conducted with data acquisition while spinning

the wheel (2 revolutions), wheel spinning without data acquisition (3 revolutions), and then data acquisition while spinning the wheel (2 revolutions). The total number of wheel revolutions in a typical WAE was therefore seven. The wheel rotation rate was 1 cm/sec; and five readings were obtained from each coated sample in each wheel revolution. The central, or peak, reading of each sample was, by design, unaffected by light reflected from any adjacent samples.

The data returned by the WAE included the rover X and Y positions, rover heading, X and Y accelerations, left and right bogies potentiometer telemetry, error flags, wheel motor current, and photodetector voltage. The right bogie arm potentiometer and the differential potentiometer resistance was acquired at several intervals during a WAE to reveal the angular positions of the WAE bogies. The intervals were usually at 0, 2, 5, and 7 revolutions of a WAE. The depth of dig of the wheel abrasion wheel was then calculated by trigonometric relations from these potentiometer results.

Some WAEs were conducted with a "lift" WAE. A lift WAE was conducted by driving the right front wheel back a ¼ turn then driving the right rear wheel forward a ¼ turn which elevates the center, wheel abrasion, wheel. The photodetector data was acquired while the wheel is spun. The purpose of the lift WAE was to evaluate wear by obtaining a "clean" signal from the wear strips. A lift WAE was conducted on sols 39 and 53.

GROUND WAE PROCEDURE

Ground tests were conducted under simulated martian conditions for comparison with flight data. A cylindrical vacuum chamber about 600 mm in diameter by 600 mm long was modified to accommodate an appropriately loaded WAE wheel, a WAE photodetector, and a circular tray for the wheel to roll in, and a light source of approximately solar spectrum to reflect from the wheel strips.

A variable speed electric motor, external to the vacuum chamber, rotated the wheel which, in turn, drove the turntable filled with martian surface simulant. The wheel was driven at 1.0 rpm which fell within the typical wheel speed of the rover on Mars: 0.6 to 1.2 rpm. The slip between the wheel and the surface simulant in the turntable wore the metal films. The slip was calculated to be 5 to 15 percent for the simulants tested, and could be adjusted by means of an electromagnetic brake. The load on the wheel for the ground tests equaled the average load on one wheel of the rover in martian gravity, 7.8 N.

A capacitively coupled electrostatic voltmeter measured the electrostatic charging of the wheel in the dry conditions of the test facility. The electrostatic probe could be raised or lowered while the test facility was under vacuum to view the ground plane. The ground plane served as a reference to zero but the electrostatic voltmeter since the ground plane was electrically connected to earth ground.

A xenon arc lamp was the light source, since it is spectrally similar to the sun. The light was specularly reflected from the wear strips onto the photodetector. For the laboratory tests, the photodetector was located the same distance from and had the same orientation with respect to the wheel as on the flight experiment.

Before conducting the wear tests, the ground test facility was pumped down to 1×10^{-3} Pa with a diffusion and mechanical pump and then backfilled with a simulated

martian gas mixture (in percent: 95.6, CO_2; 2.52, N_2; 1.36, Ar; 0.336, O_2; 0.153, CO; and 0.03, H_2O [8]) to average martian surface atmospheric pressure 0.71 Pa (7 mbar) at room temperature, 23°C. Five martian surface simulants were used for the ground testing. The median grain sizes of these five simulants ranged from 6 to 2000 micrometers. The simulants filled the cavity in the turntable. Each simulant was used in a separate wear test.

RESULTS AND DISCUSSION

Depth of Dig

The WAE depth of dig (DOD) was calculated based on the angles of the two bogie arms at the start and end of the wheel abrasion sequence. The DOD is defined as the movement of the WAE wheel in the +z direction (toward the bottom of the rover). The formula is given by:

$$DOD = r_\alpha[\sin(\alpha_o + \alpha_2) - \sin(\alpha_o + \alpha_1)] + r_\beta[\sin(\beta_o - \beta_2) - \sin(\beta_o - \beta_1)]$$

where: $r_\alpha = 20$ cm

$r_\beta = 12$ cm

$\alpha_o = 30°$

$\beta_o = 45°$

α_1 = differential angle of bogie at start of sequence

α_2 = differential angle of bogie at end of sequence

β_1 = right bogie angle at start of sequence

β_2 = right bogie angle at end of sequence.

Figure 4 shows the DOD for all WAEs except sols 28, 39 and 53, since they were lift WAEs. The dig data fall into three general categories: rock-like or very hard soil material (sol 14 and 18), somewhat softer material (sols 4.1, 4.2, 5, 12, and 21) and loose soil (sol 23) [9]. Sol 14 was taken on a feature named Scooby Doo and sol 18 data was taken in the vicinity of the feature named Cabbage Patch. There is no appreciable DOD after seven revolutions at either location. The WAE in the softer material (sol 4.1, 4.2, 5, 12, and 21) all exhibit a similar dig profile, digging 0.6 to 0.7 cm in the first two revolutions. The rate of dig then begins to decrease with a final depth of 0.8 to 1.2 cm after seven revolutions.

The sol 5 experiment was conducted on the morning following the sol 4.2 experiment. Since the rover was not moved between these two experiments, the WAE wheel began the sol 5 test in the hole left by the sol 4.2 test. The dig rate in sol 5 follows the profile established in the sol 4.2 test. The sol 23 WAE test was conducted in the vicinity of a rock called Snowy. The wheel dug 1.5 cm in two wheel revolutions so the material was very loose. The sol 4.2/5 and sol 23 data seem to indicate an asymptotic dig depth of about 2 cm, perhaps because of the presence of a hard, crust-like material at that depth. In preflight ground tests, the WAE wheel was able to dig greater than 3 cm in loose surface simulant in a few revolutions, suggesting that dig depth on Mars was not limited by rover mechanical characteristics, and that the martian dust is much more compacted only a few centimeters beneath the surface than it is at the surface.

Dust Adhesion

The lander camera provided evidence of dust accumulation on the Sojourner rover wheels [9]. Also, during WAEs, dust depressed the reflectance signals. Figure 5 shows the rover on sol 3 before dust accumulation was first noticed on the wheels. Figure 6 shows severely depressed signals of some platinum coupons and all aluminum coupons of the first WAE on sol 4. This signal reduction is a result of dust adherence rather than metal film wear since a later WAE from sol 53, Fig. 7, shows Pt and Al peak values higher than in Fig. 6. The sol 22 end-of-day image, Fig. 8, shows fine red dust concentrated around the wheel edges with additional accumulation in the wheel hubs. Images on sol 4 of the rover illustrate the loss of black-white contrast on the wheel abrasion experiment strips. Loss of contrast was also seen on test wheels in the laboratory from dust adhesion.

In laboratory tests with five different soil types, grain sizes less than 25 micrometers resulted in severe wheel clogging. The mass of adhering dust to the wheel was inversely related to grain size for the five simulants tested. Similar clogging may also be seen in Fig. 8 on the martian surface. The smooth and reflective tracks of the Sojourner wheels in the soil are produced in soils with a grain size of 40 micrometers or less [10].

Abrasive Wear of Wheel Strips

As the rover traversed the martian landscape, a total of eleven (11) WAEs were conducted as shown in Fig. 9. Ideally, Sojourner was pointed in the direction that would result in the best specular reflection from the sun, and the change in the value of reflected signal would indicate the amount of metal removed by abrasion from each sample. In reality, inaccurate pointing and uneven dust coating of the wheel led to difficulties in interpreting the data.

The total number of WAE wheel revolutions was 55. Of these, 16 revolutions were performed on a hard or rocky surface, where the WAE strip was probably not abraded, since the depth of dig was less than the height of the growsers on the wheel. Thus, a total of 39 wheel revolutions were conducted in wheel abrasion experiments.

Complicating the interpretation of the results was a change in the reflectance due to dust which stuck to the WAE wheel. The martian environment is extremely dry, and the WAE wheel may have been subject to triboelectric charging (static electric charging due to friction) during traverses [11]. Ground tests of a flight spare WAE wheel in a simulated martian atmosphere showed that the wheel would pick up dust and develop an electrostatic charge. When the wheel was grounded, the wheel potential fell dramatically and some dust fell off the wheel. Ground tests also showed that the magnitude of electrostatic charging increases as grain size decreases. Thus charging and dust adhesion were anticipated to be possible problems with the data analysis.

In Fig. 8, sol 53 WAE data is normalized to the calibration signal obtained before flight. The data consisted of two complete wheel revolutions, with much consistency between the two rotations [9]. The sol 53 data was then analyzed. In order to account for

the dust coating on the wheel strips, the sol 53 data was divided by the calibration signal. The reason for taking this ratio is that an even coating of dust on the samples is not expected to change the ratios much, but it will reduce overall reflectance. Ratios of the black reference samples to the calibration signal indicate the reflectivity of the black samples when covered with dust, compared to dust free condition. Since the black reference samples are aluminum oxide (impregnated with a black dye) they are expected to wear little. Plotting the ratios as a function of initial metal film thickness for the five metal thicknesses illustrate that the platinum and the nickel films have worn little while the aluminum films exhibit wear inversely related to initial film thickness.

A similar analysis was performed with ground test data. Figure 10 shows the photodetector signals of the strips from the ground tests conducted in a surface simulant with a 25 micrometer median grain size. The composition of this simulant is similar to martian soil [1]. Between the wear tests, the wheel strips were rinsed with distilled water so the photodetector signals were "clean." The strips exhibited wear in the thinnest and softest metal, aluminum, just as in sol 53. Also the peaks from thicker platinum and nickel films show little reduction at 32 revolutions, about the same number of wheel abrasion wheel revolutions as on Mars (39), justifying the normalization used.

CONCLUSIONS

One of the Mars Pathfinder Sojourner technology experiments, the wheel abrasion experiment, was designed to measure the abrasive properties of the martian surface material. Abrasion of the metal films on the wheel strips is most pronounced in the thinnest samples of the softest metal samples, aluminum, in the flight and in the ground tests. Lander images revealed adhesion of dust to the wheels. A grain size of less than 40 micrometers is inferred from the clogging of the dust in the wheel on Mars. Ground tests, conducted using five simulants with grain sizes from 6 to 2000 micrometers in a simulated martian environment, revealed electrostatic charging and adhesion of dust to the wheel. The depth-of-dig of the wheel abrasion wheel on Mars shows that in some WAEs the digging rate decreases at a depth of about 1-2 cm, suggesting a harder, compacted material beneath the 1-2 cm of loose dust.

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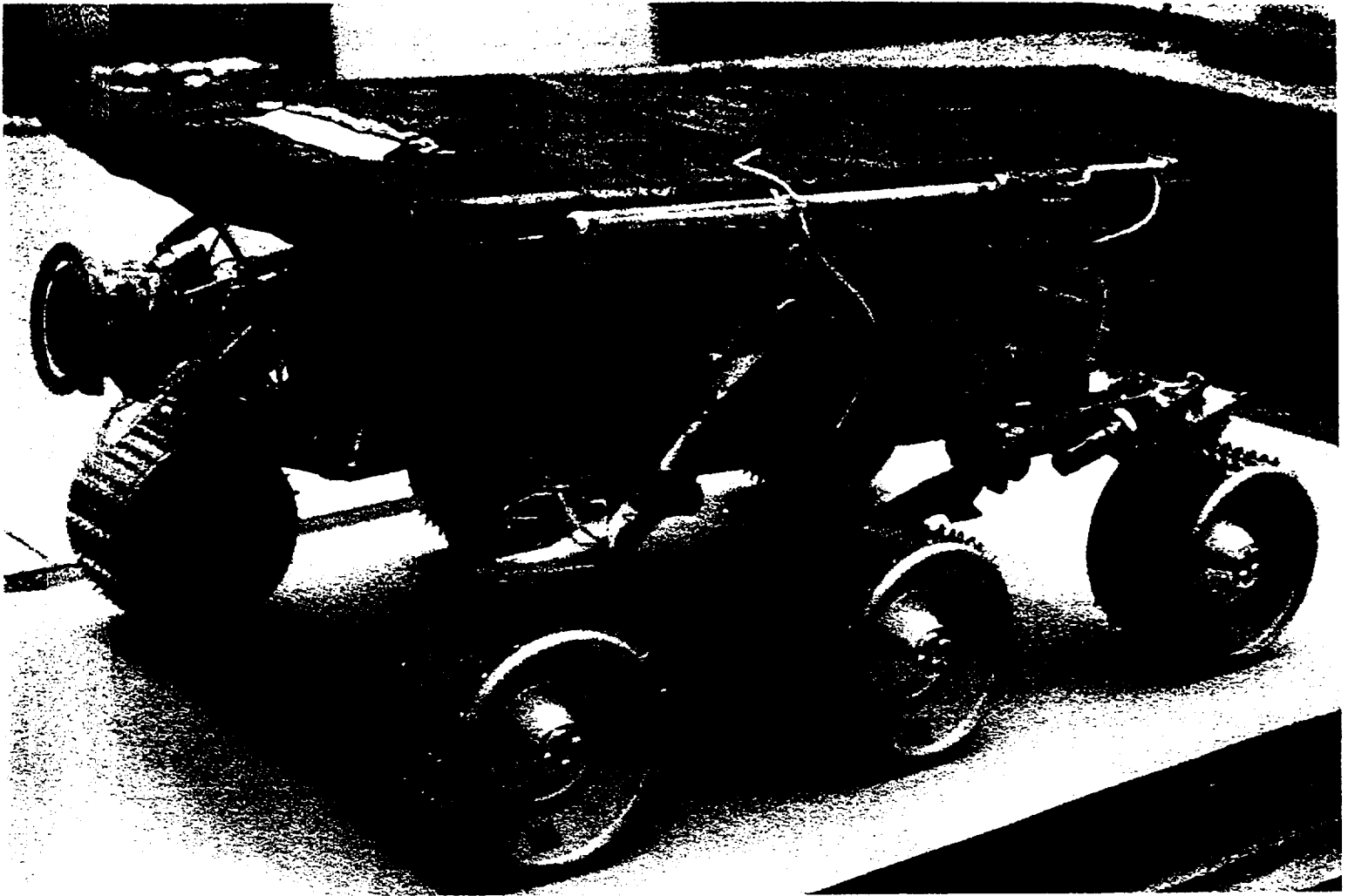
Figures

Fig. 1--The right center wheel of the rover is the wheel abrasion wheel. The piece of amber tape on the bogie arm, near the wheel abrasion wheel, covers the apertures of the photodetector.
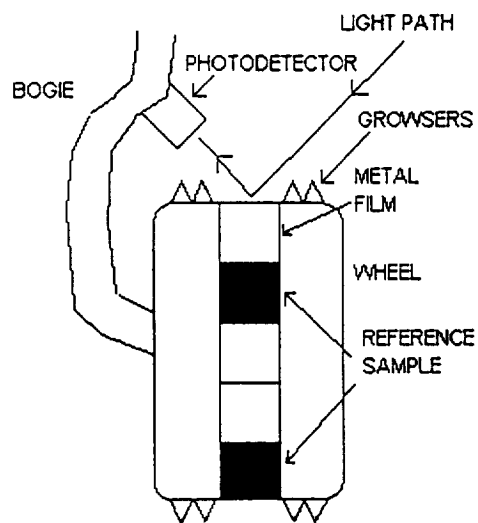
Fig. 2--Schematic of wheel abrasion experiment. As the wheel rotates, the photodetector views either metal films samples or black reference samples.
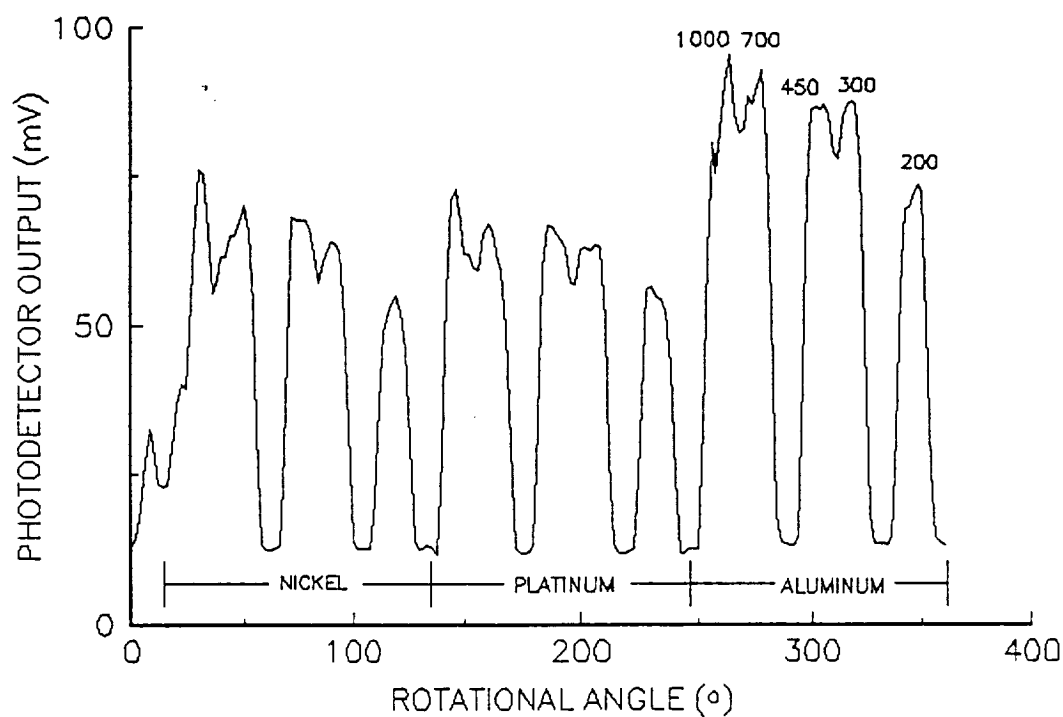
Fig. 3--Photodetector output of flight wheel abrasion wheel before conducting a wheel abrasion experiment, called calibration data. The metal of the films is labeled under their corresponding peaks. The numbers above the peaks represent the initial film thickness in Angstroms of Al. The film thicknesses for Pt and Ni have the same pattern as Al. The single peak corresponds to the 200 Angstrom thick metal film.
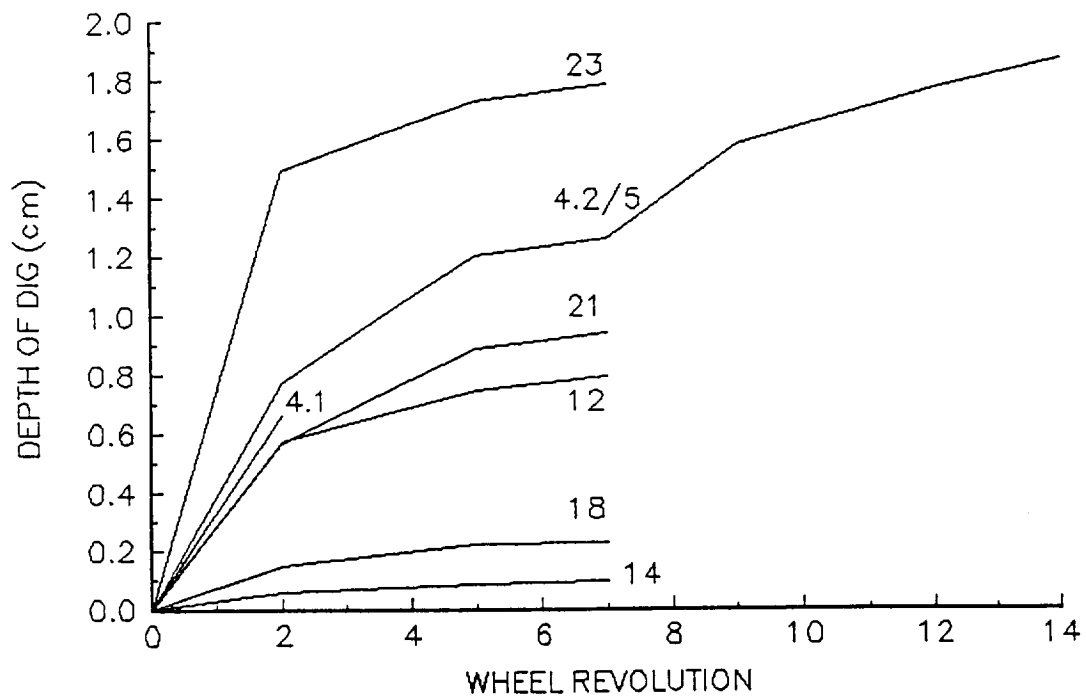
Fig. 4--Depth of dig of wheel abrasion wheel versus wheel revolutions for the entire WAE data set when the WAE wheel was in contact with the surface. The curves are labeled according to the sol in which the WAE was conducted.
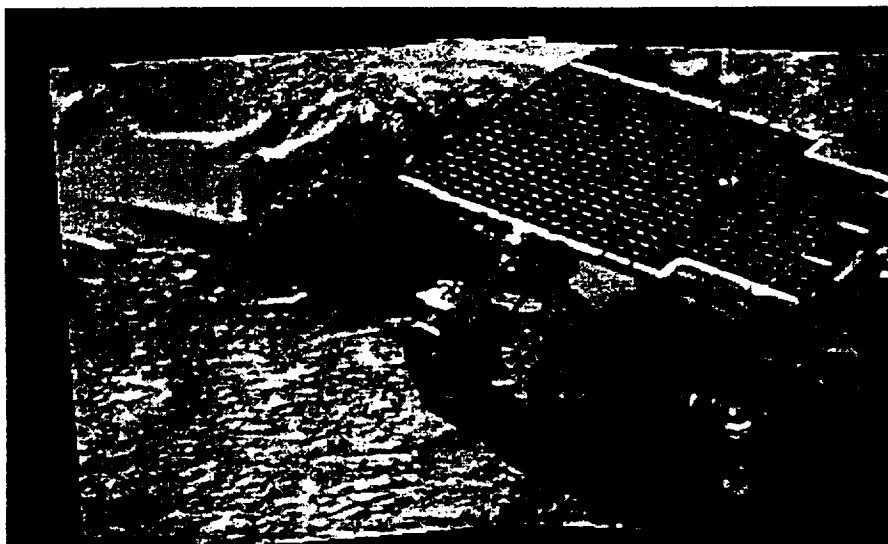
Fig. 5— The rover on sol 3 before dust accumulation was first noticed on the wheels on sol 4.

Fig. 6—Normalized sol 4.1 reflectance signals, compared to preflight calibration of Fig. 3. Dust coverage starts with the 300 and 450 Å thick platinum peaks and includes all the aluminum peaks.

Fig 7--WAE photodetector output of sol 53 compared to the preflight calibration. Two revolutions of data is shown. The sol 53 data is normalized by the peaks of the thick Ni films. The peaks associated with the metal films are labeled.

Fig. 8--Image of rover showing adherence of red surface material to wheels.

Fig. 9—Locations of all WAEs by sol. Grid squares are 1 meter on a side.

Fig. 10—Photodetector output from the ground tests of wheel abrasion wheel at several equivalent wheel sliding revolutions conducted with the 25 micrometer grain-size simulant. The numbers in the legend represent the number of equivalent sliding revolutions of the wheel. The output was normalized by the values of the black reference coupons (the valleys).

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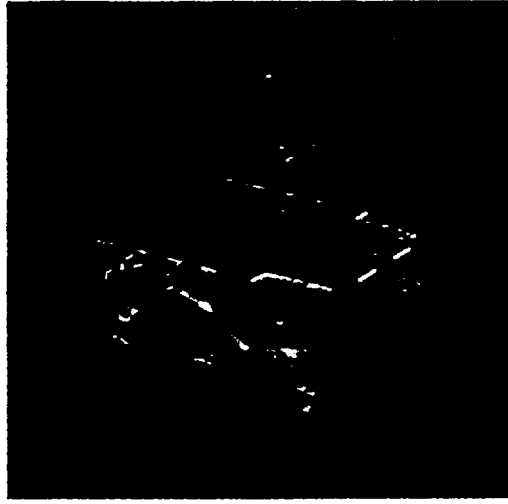
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figure8wae.bmp (256x285x16M bmp)

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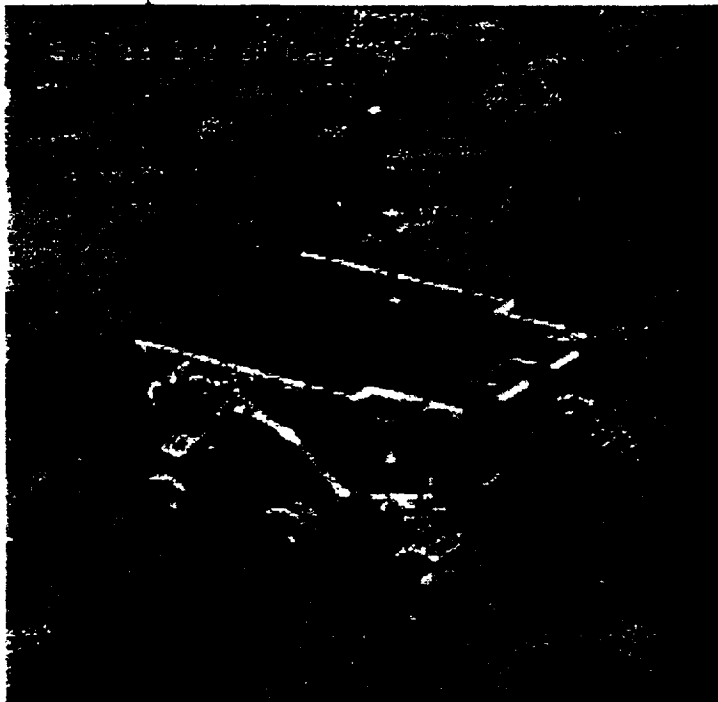

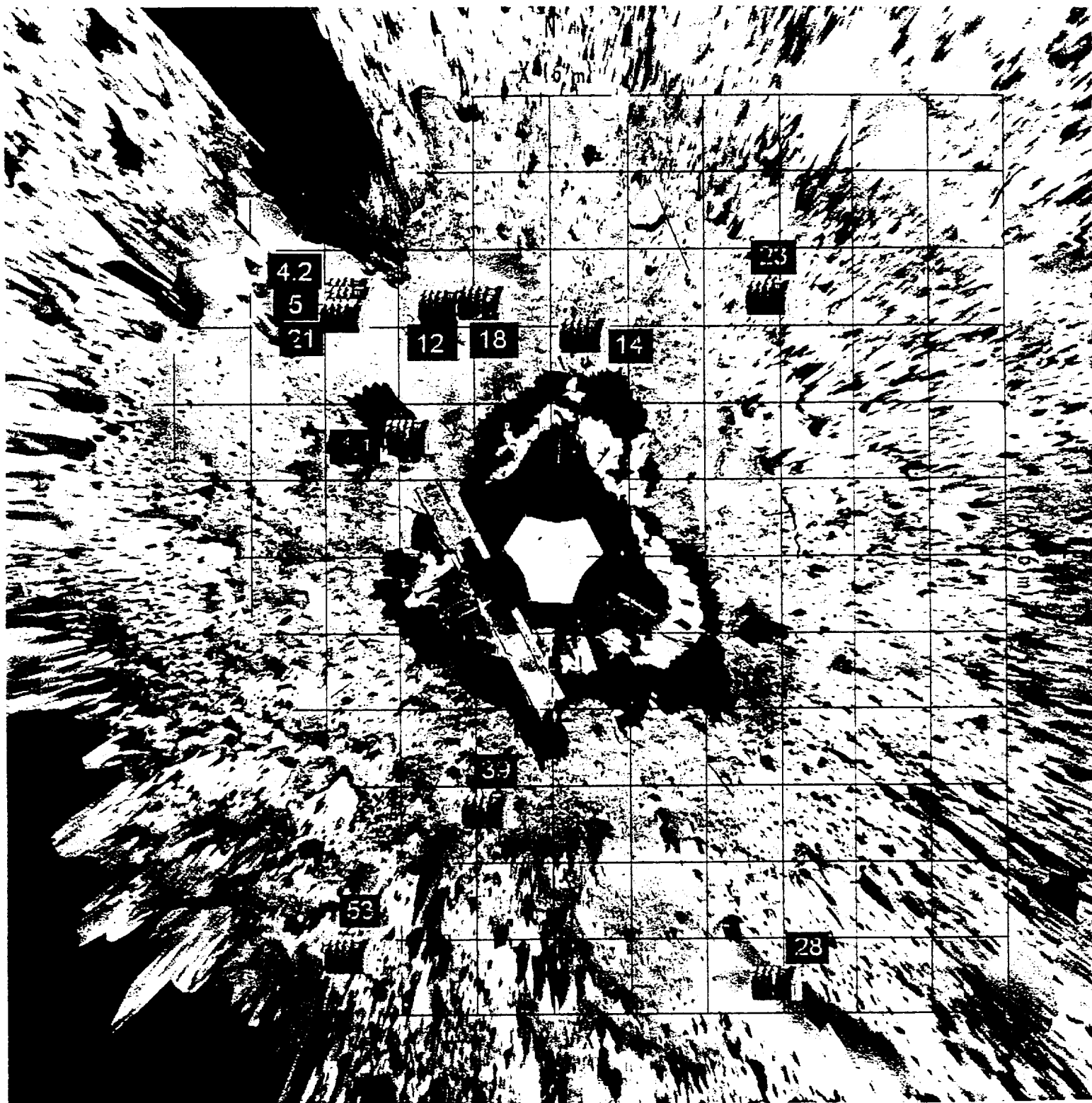Fig. 8--Image of rover showing adherence of red surface material to wheels.

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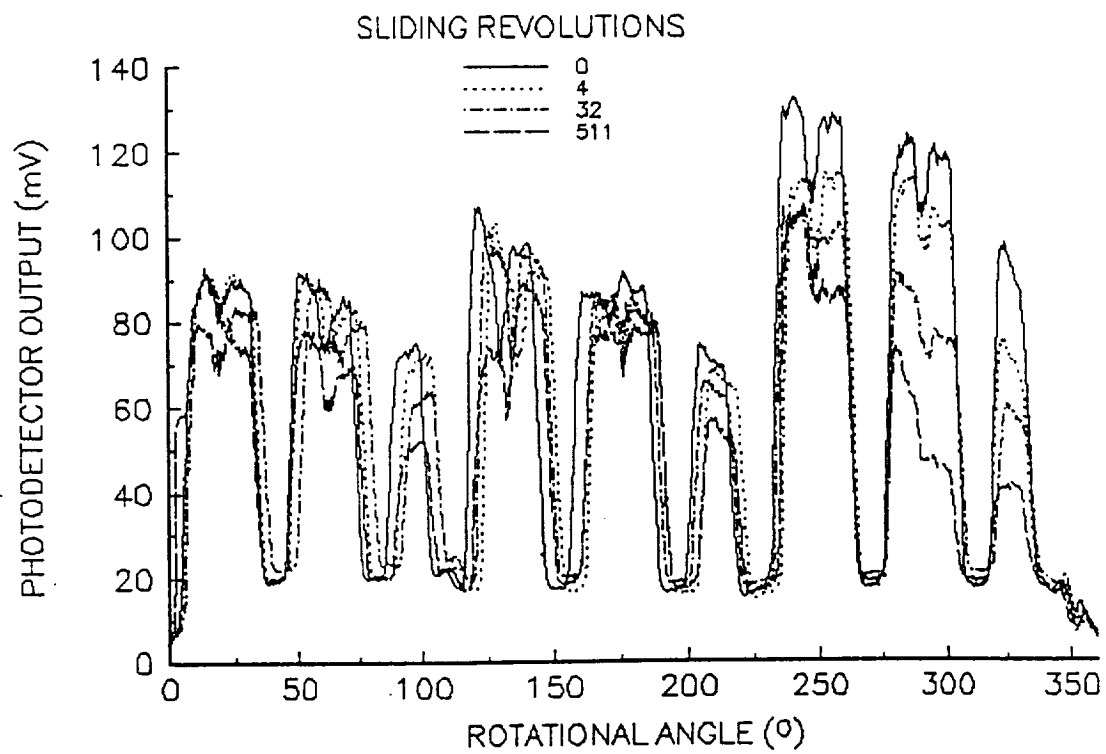

SLIDING REVOLUTIONS

Fig. 10—Photodetector output from ground tests of wheel abrasion wheel at several equivalent wheel sliding revolutions conducted with the 25 micrometer grain-size simulant. The numbers in the legend represent the number of equivalent sliding revolutions of the wheel. The output was normalized by the values of the black reference coupons (the valleys).