SIMULATION OF MARS SURFACE CONDITIONS FOR CHARACTERIZATION OF THE MARS ROVER THERMAL RESPONSE

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ABSTRACT

The Mars Rover is a robotic vehicle which will be used to explore the Martian surface when it arrives on Mars as part of JPL's Mars Pathfinder mission. On Mars, the Rover will be subjected to temperatures as low as -100"C and wind speeds as high as 20 meters/sec in an atmosphere comprised primarily of C02 at a pressure of 6 to 8 torr. To verify the Rover design, JPL engineers needed empirical data to study the Rover's thermal response to simulated Mars surface environments. To obtain this empirical data, a thermal-vacuum test was devised to emulate the environmental conditions that the Rover would be expected to endure during both days and nights on the Mars surface. Unique to this test was the need to create wind within a thermal vacuum chamber at 8 torr and at varying low temperatures. An engineering model of the Rover (Rover-EM) was constructed and used as the test article of this test. This paper describes the mechanical equipment used to produce a simulated Martian surface environment, including wind, in a vacuum chamber, and, discusses the results of tests using this equipment.

Keywords: Mars Rover, Mars Environment

INTRODUCTION

The Mars Pathfinder spacecraft is currently being built at JPL and is a Mars lander mission. The lander module houses the Rover (see Figure 1) as well as other instruments to sample and analyze the Mars surface composition and environment. When the spacecraft approaches Mars, the cruise stage will be jettisoned and the lander module will enter the Mars atmosphere and descend towards the Mars surface. A 12.7m diameter parachute (Dacron canopy with Kevlar suspension lines) will deploy at 10 km above the surface to aerobrake the rate of fall and a four-pod Kevlar airbag system will deploy within 100 m of the surface to cushion the lander impact at touchdown. Once the airbag-cushioned lander has come to rest on the surface, the air-bag will deflate in about 1.5 sec and will retract towards the lander in 1.7 hr using a cable-reeling winch system.

The lander is a tetrahedron which has three side "petals" and a base. Once the airbag has retracted, the lander will open like flower petals blossoming (the retracted Kevlar will cushion the petals as they open) and the instruments and Rover housed inside will be exposed to the Martian environment. Figure 2 shows this landing sequence.

Because the JPL thermal engineers needed verification of the thermal response of the Rover to this harsh environmental exposure, a test plan was devised to subject the Rover-EM to a simulated Martian surface environment in JPL's 10-ft Space Simulator, The test plan objectives were: 1) to demonstrate that the Rover thermal design effectively maintains the temperature of all components within critical ranges for cases when the Rover is a) stowed and b) unstowed and operating; 2) to demonstrate the Rover functional performance and, concurrently, to qualify the performance of Rover components in applied nominal Martian environmental conditions; and, 3) to assess the Rover sensitivity to off-nominal Martian conditions (.same temperature profiles but with wind speed at about twice nominal).

The testing was planned to occur in three phases:

SIM-Q1: calibration of the wind speed vs. motor rpm followed by a steady state thermal vacuum test representing the cruise stage of the spacecraft near' Mars before landing;

SIM-Q2a: with the Rover stowed, test the thermal response in nominal diurnal transient temperature conditions;

SIM-Q2b: with the Rover unstowed, test thermal response in nominal diurnal transient temperature conditions;

SIM-Q3: with the Rover stowed, test thermal response in off-nominal diurnal transient temperature conditions.

TEST SETUP

A test fixture was designed to simulate the diurnal Mars environment including the Mars surface temperature, the near-surface gas temperature, the sky temperature at both day (solar) and night (night sky) conditions, and wind at varying speeds. The test fixture included: 1) a temperature controlled copper base plate to simulate the temperature of the exposed petal on which the Rover is mounted (the base plate closely follows the Mars

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ground temperature); 2) a temperature-controlled sky plate to simulate the diurnal sky temperature; 3) a wind generating machine to simulate wind at 6 m/sec and 12 m/sec; and, 4) a temperature controlled compensator plate to assist in controlling the temperature of the gas being drawn through the wind machine and blown towards the Rover-EM. Figure 3 schematically illustrates the test fixture. Figure 4 is a close-up photo of the test fixture with the Rover mounted in place. Details of the wind machine drive linkage are described below and are illustrated in Figure 5. A temperature-controlled chamber wall and floor shroud system served to condition the 8 torr GN2 in the chamber to Mars-like temperatures.

WIND MACHINE DESCRIPTION

Creating wind in an 8 torr environment was a challenging undertaking. A motor-driven fan was selected as the mechanism to generate the wind. An 8-blade, 762 mm (30") diameter stainless steel (SS) fan was driven by a three phase, 8-pole carbon brush, 5 Hp dc motor with a 31.75 mm (1.25") SS shaft. This motor was selected primarily because it was readily available at no cost. A magnetic sensor measured shaft rpm and a constant speed logic circuit was used to control motor speed up to 1600 rpm. To protect the motor from the cold temperatures and the low pressures of the simulated Mars environment, it was necessary to mount the motor inside a sealed canister [304.8 mm (12") ID, 762 mm (30") long, with 381 mm (15") OD flanges on each end]. The enclosed motor was cooled with a temperature-controlled GN2 gas stream fed through a 12.7 mm (0.5") SS flexhose directly into the motor frame then vented out the canister to atmosphere,

The motor drive linkage included a SS transition [31.75 mm/19.05 mm (1.25"/0.75"), a 19.05 mm (0.75") standard brass coupling, a 19.05 mm (0.75") SS water-cooled Ferrofluidics rotary seal, and a SS 19.05 mm/31,75 mm (0.75 "/1 .25") transition which linked directly to the fan hub. Linkages were keyed and the keys on the transitions were able to be tightened in place with a pair of set screws. The coupling also had one set screw which locked the coupling to the shaft. Linkage details are shown in Figure 5.

To ensure vibration-free operation, the canister was bolted securely to a 381 mm (15") OD, 24-hole flange which was welded to 152.4 mm (6") wide, 12.7 mm (0.5") thick aluminum crossbars and centered at the horizontal centerline of the upstream side of a rigid structural frame [1650 mm (65") H x 1752 mm (69") W x 2032 mm (80") L] fabricated from 101.6 mm (4") square aluminum bar stock. The fan was enclosed in a 813 mm (32") diameter SS sheetmetal housing which was swaged down to a 559 mm (22") diameter at the wind discharge plane. A 559 mm (22") diameter, 12.7 mm (0.5") thick sheet of SS honeycomb with 6.35 mm (0.25") holes was attached at the discharge plane to direct the wind uniformly towards the Rover-EM. A conical wind diffuser [838 mm (33") base diameter, 432 mm (17") long] was installed at the downstream end of the structural frame to distribute the circulating gases evenly and to minimize the possibility of back-flow buffeting of the wind against the Rover-EM. The Rover-EM was mounted on a temperature-controlled copper base plate and was centered in-line with the wind discharge plane facing the wind. A 2946 mm (9'-8") diameter mylar covered disk barrier frame was mounted above the structural frame to help keep the circulating gas contained in the lower portion of the vacuum chamber. Finally, a fan intake cone 686 mm (27") diameter swaged to 381 mm (15") diameter) was installed around the canister to help smooth and direct the intake gas flow stream to the the fan.

The wind speed calibration was done using a hot-wire anemometer which was an engineering model of the Mars Pathfinder Wind Sensor (ASI/MET). Two reference plates (one gold foil surface and one black paint surface) were installed as a back-up to the hot-wire anemometer to provide a "sanity check" of the actual chamber conditions as well as to help with the evaluation of the heat transfer correlation calibrations. The reference plates were mounted above the rover solar panels, the gold plate followed by the black plate (see Figure 4).

PRIMARY TEST EVENTS

The Rover-13M test was fraught with challenge, At almost every step in the test plan, the operators were faced with problems that required rapid remedial action. Equipment failures coupled with trial and error operator judgments made this test an unforgettable experience. We learned that creating a simulation of a Martian surface environment is more difficult than one might imagine.

The test began on the morning of 10/22/95. The initial attempt at evacuation of the chamber with the axial compressor failed because at the onset of pumpdown, the primary chamber door o-ring was not seated properly. Four hours later, after reseating this o-ring, the pumpdown was started again but the chamber pressure leveled at about 4 x 10^{-2} torr indicating a leak. A small leak was found at the feedthrough for the motor controls so the chamber was backfilled to ambient pressure with GN2 and this feedthrough flange was replaced with one that was tested to be non-leaking. When the third purnpdown attempt started, the large vacuum valve which isolated the axial compressor would not open, so the pumpdown commenced with only the mechanical roughing pumps, which added an additional 45 minutes to the normal purnpdown time. Again, the chamber pressure leveled at about 4 x 10^{-2} torr. When the motor housing cooling gas flow was turned on, the chamber pressure rose quickly to about 0.2 torr, indicating a GN2 leak from the motor housing. It was decided that this leak would not interfere with the testing at 8 torr when motor cooling would be required so the test was continued. Also, it was discovered at this point that the maximum achievable cooling gas flow rate to the motor housing was lower than expected and that a 0.25" flex hose attached to the motor housing was choking the flow.

Checkout of the other heat exchanger circuits commenced. It was discovered that both solenoid valves controlling LN2 flow to the compensator plate were leaking and that the valve cluster needed to be replaced. This replacement was postponed until 10/23 AM. Other circuits were working properly.

With the motor housing cooling gas flowing, the motor was started so that the ferrofluidic seal cooling water system could be checked out. It was observed that the ferrofluidic seal temperature was not being cooled because of a failure of the cooling water pump. A replacement cooling water bath was quickly plumbed in and this system worked properly.

Next, it was noticed that the video camera image was streaking. This corrected when the camera was warmed a few degrees. With all systems checked out, the pumpdown was stopped, the chamber backfilled with GN2 to 8 torr and further test activity was postponed until the following morning.

SIM-Q1: The SIM-Q1 test began on 10/23 with a calibration of windspeed vs. motor rpm with the chamber at room temperature and pressure, At the beginning of the calibration, the motor speed was raised to 1600 rpm fairly rapidly and was operated at that speed for a period of about 15 minutes before it was noticed that the motor housing temperature had exceeded 40 "C (a motor operation maximum). To compensate for this overheated condition, the motor speed was reduced to 1200 rpm and the motor housing cooling gas temperature was lowered. About two hours were expended performing the calibration but measurements were unsteady and the results inconclusive.

The Mars diurnal day test schedule made it necessary to proceed with the test plan without conclusive wind speed calibration data. It was decided to use the reference plates for wind speed calibration. To simulate the near-Mars approach, all heat exchangers were cooled to -35 "C and kept at that temperature until 2:00 AM on 10/24. The chamber pressure was lowered to <1 x 10^{-5} torr after feedthrough plumbing connections to the canister were disconnected and capped to prevent GN2 leakage.

At 2:00 AM on 10/24, the chamber was backfilled to 8 torr with GN2 and the simulation of the diurnal temperature profiles of the Martian surface and sky began. Temperature adjustments were made to the wall and floor shrouds, the skyplate, and the mounting plate (Martian surface). The compensator plate was operated intermittently until it was decided that it had a minimal effect on the circulating gas temperature. The fan was turned on at 2:30 AM and set at 800 rprn. Around 7:00 AM, it was noticed that the fan was not turning even though the motor was still running and rpm measurements still registering. Shortly thereafter, a decision was made to abort the test and investigate the wind generation machine problem. Subsequent analysis of Ferrofluidics seal and motor frame temperature data showed telltale major spikes in temperatures at about 6:30 AM. Directly thereafter the motor frame temperature dropped abrubtly. This data clearly indicates that the decoupling occurred at about 6:30 AM.

By 11:15 AM, the chamber had been warmed, backfilled and opened. When the canister cover flange was removed, it was observed that the entire canister interior was coated with carbon powder -- ostensibly from wear of the carbon brushes in the motor. Additionally, it was discovered that the coupling had decoupled and the coupling half nearest the Ferrofluidics seal had moved forward on the Ferrofluidics shaft away from the motor. Figure 6 shows this coupling separation. This decoupling explains why the motor could still be turning while the fan was not. It also helps explain the abrupt temperature drop of the motor frame since there was no longer a load on the motor. The motor was removed and inspection of the brushes confirmed that they were badly worn. Figure 7 shows the condition of the brushes that were removed from the motor.

New motor brushes were installed, a stainless steel collar was mounted on the Ferrofluidics shaft to limit the travel of the coupling to prevent a recurrence of the decoupling problem, all the carbon dust was cleaned from inside the canister and the motor linkage was reassembled and remounted inside the canister. Also, the 6,35 mm (0.25") flex hose feeding the cooling gas to the motor housing was replaced with a 12,7 mm (0.5") flexhose to allow an increased flow of GN2 to the motor housing. By 9:15 PM all repairs had been completed and GN2 and water connections were remade in preparation for the continuation of the test. Pumpdown commenced again by 10:45 PM. By midnight the chamber had been conditioned to 8 torr and resumption of the Martian temperature profiles began immediately thereafter.

SIM-Q2a: The fan was turned on and set at 500 rpm and kept at that speed until 8:00 AM on 10/25 when it was raised to 800 *rpm*. Wind speed calibration again was attempted using the ASI/MEI sensor, but again the results were very unstable and inconclusive. The wind machine continued to operate at 800 rpm until about 2:00 AM on 10/26, when it failed again. Later investigation showed that again the failure was attributable to coupling separation and carbon brush deteriorization. It was also observed that the Ferrofluidics shaft near the coupling was badly worn presumably caused by excessive wear at the key/keyway interface. The SIM-Q2a portion of the test was concluded at about 1:30 PM on 10/26 when the Rover was unstowed.

SIM-Q2b: The testing of SIM-Q2b was to simulate the Rover operations after unstowing, i.e., after stand-up from the petal. Because of the wind machine failure, the entire SIM-Q2b testing was conducted under no-wind conditions and was concluded at 8:15 AM on 10/28.

SIM-Q3: Since the purpose of the S1 M-Q3 test was to study the thermal response of the Rover-EM at higher windspeeds, SIM-Q3 was cancelled since the wind machine had failed.

TEST RESULTS

The prescribed nominal Martian sky temperature profile for SIM-Q2a is given in Figure 8a and profiles for the surface and surrounding environment are given in Figure 9a. Measured profiles for the sky and for the surface/surrounding environment are shown in Figures 8b and 9b.

The prescribed nominal Martian sky temperature profile for SIM-Q2b is given in Figure 10a and profiles for the surface and surrounding environment are given in Figure 11a. Measured profiles for the sky and for the surface/surrounding environment are shown in Figures 10b and 11b.

It can be seen that despite the many problems that were encountered during the Rover-EM test, the Mars environmental conditions were simulated fairly well. What was lost because of the wind machine failure was an accurate approximation of the heat transfer coefficients of the various wind-exposed Rover surfaces and components. However, since both wind and no-wind conditions existed during the test, enough data was gathered to allow the thermal engineers to conclude that the Rover-EM can adequately withstand the predicted worst case scenario Martian environmental conditions.

CONCLUSIONS

Simulation of the Mars surface environment, especially wind, is difficult to attain. Generating wind in a partial vacuum requires careful selection of the motor and design of the drive train linkage. We used a motor with carbon brushes instead of a brushless motor, primarily because this motor was available without cost. Also, using GN2 instead of air to cool the motor probably contributed to the rapid carbon brush wear, The GN2 probably served to embrittle the carbon by drying it out and consequently increasing the wear rate. Also, it has been suggested that the carbon brush interface with the motor commutator may require air to establish a lubricating 02 or C02 plasma layer between the brushes and the commutator to limit rapid wear of the brushes. The effects of thermal cycling on the linkage elements need to be better understood so that linkage fasteners (set screw, etc.) can be designed against failure.

If there is a future requirement for creating wind at similar low temperature and pressure conditions, it is recommended to use a brushless motor, to cool the motor with air, to be doubly certain that the canister seals are all leak tight before chamber evacuation, and to more adequately secure all components in the drive train against slippage and failure.

Even though the equipment and operators were very challenged during this test, and problems abounded, the outcome of the test was relatively positive. The thermal engineers obtained useful empirical data, enough so that they were able to verify that the thermal design of the Rover-EM was effective in maintaining critical components within acceptable temperature bounds.

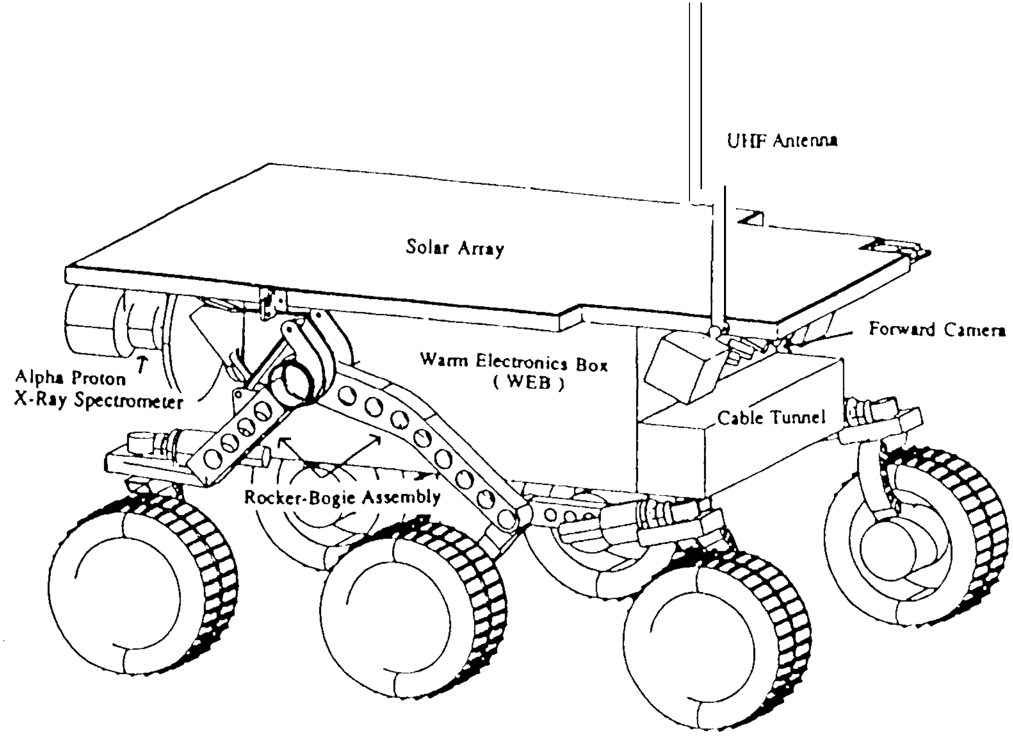


Figure 1a. Schematic of the Mars Rover

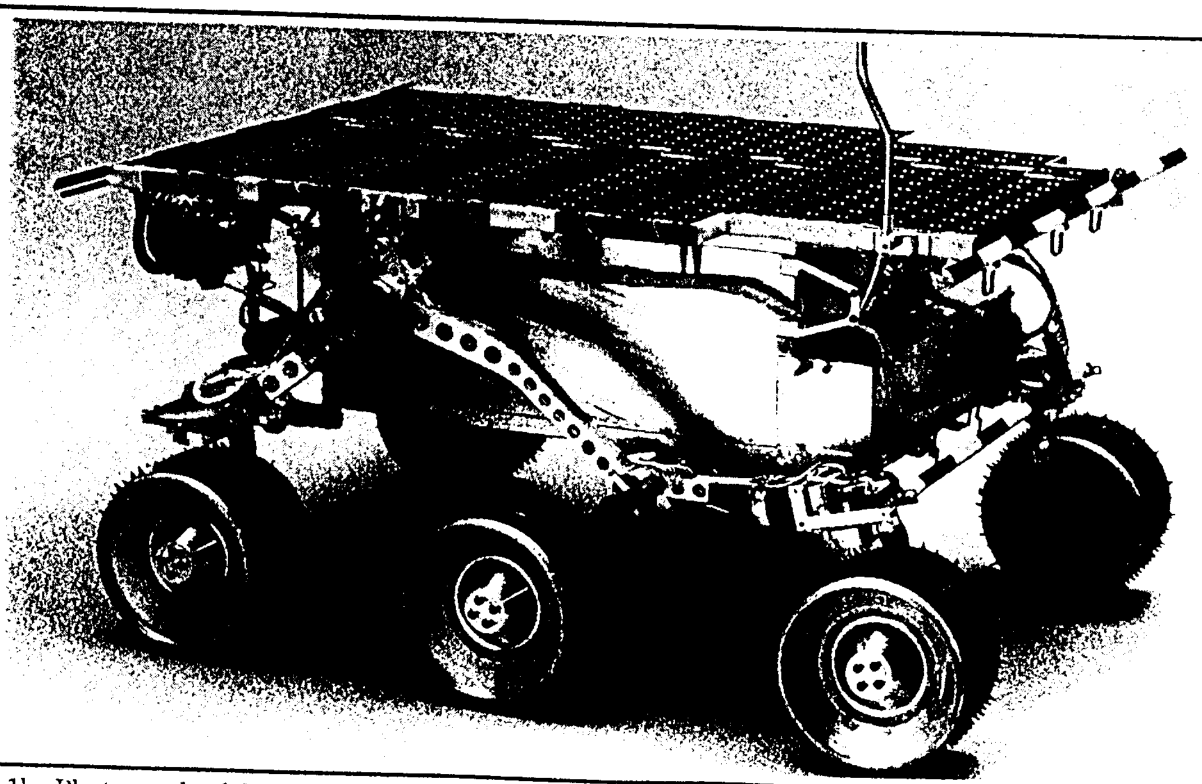


Figure 1b. Photograph of the Mars Rover

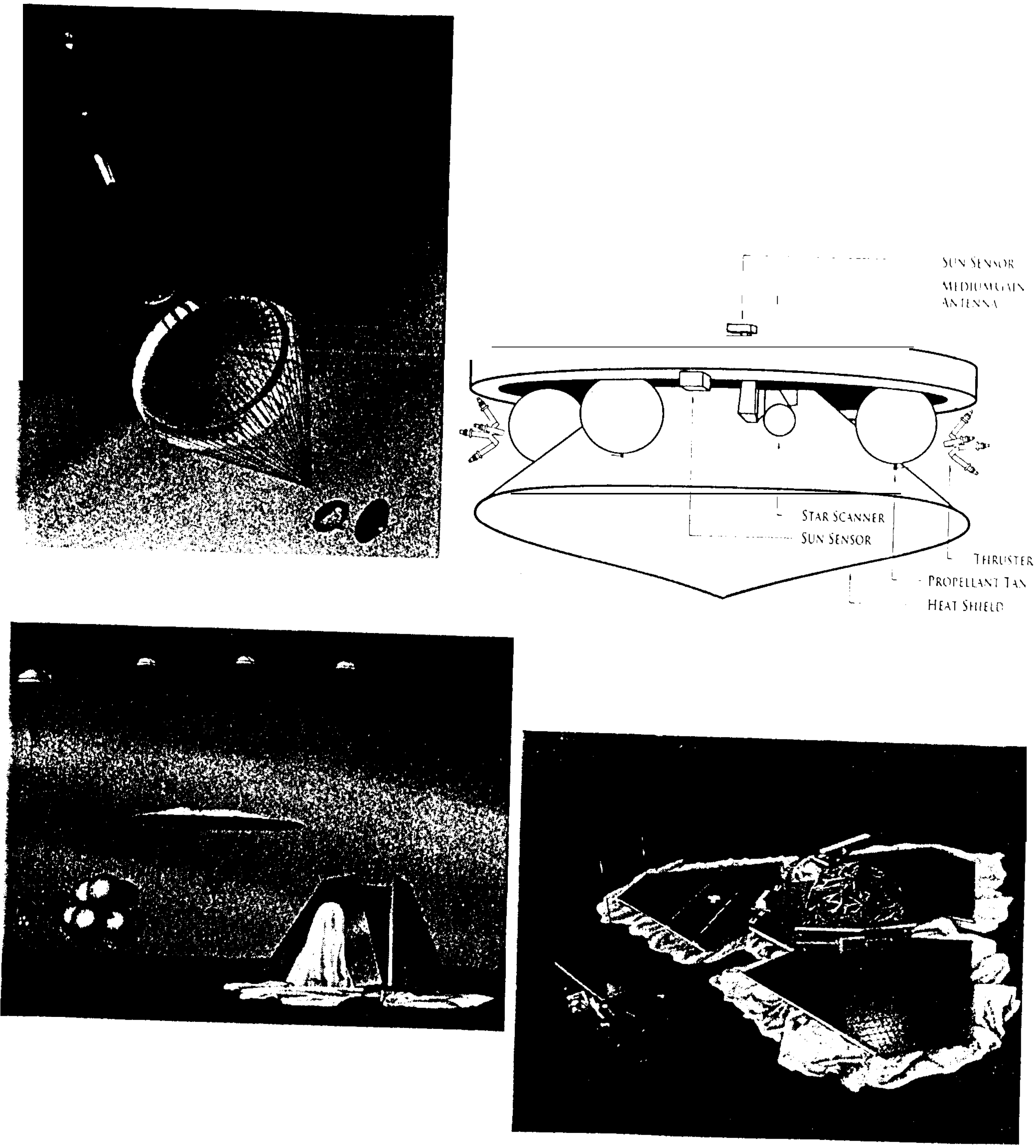


Figure 2. Mars Pathfinder Landing Sequence

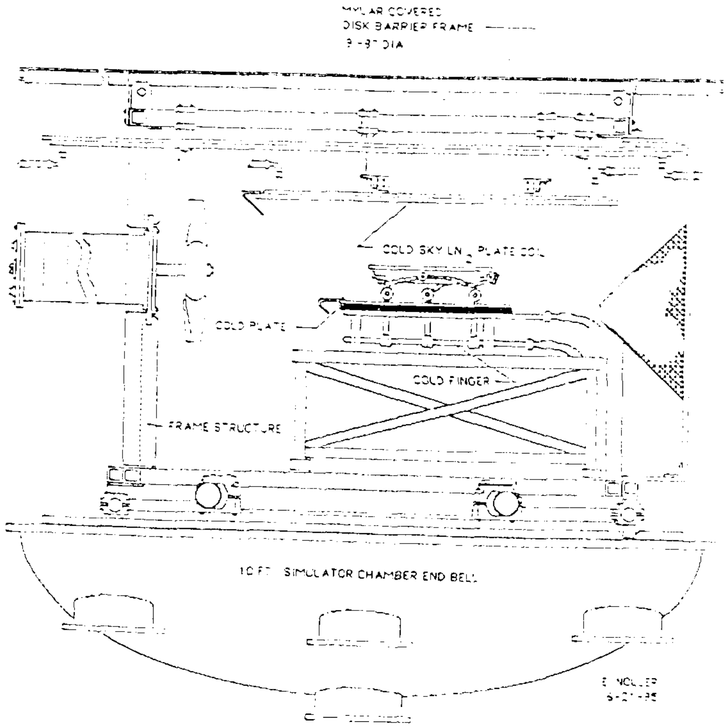


Figure 3. Mars Surface Wind Generation System

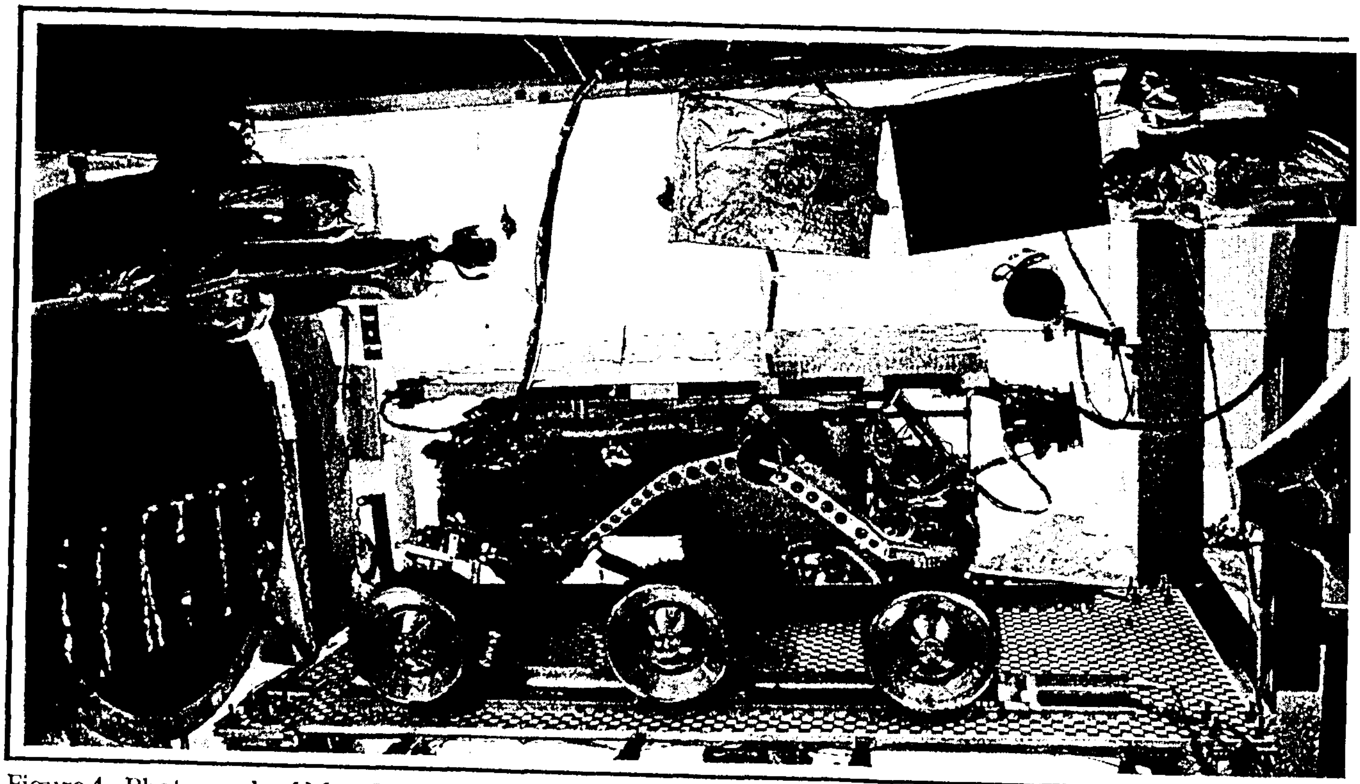
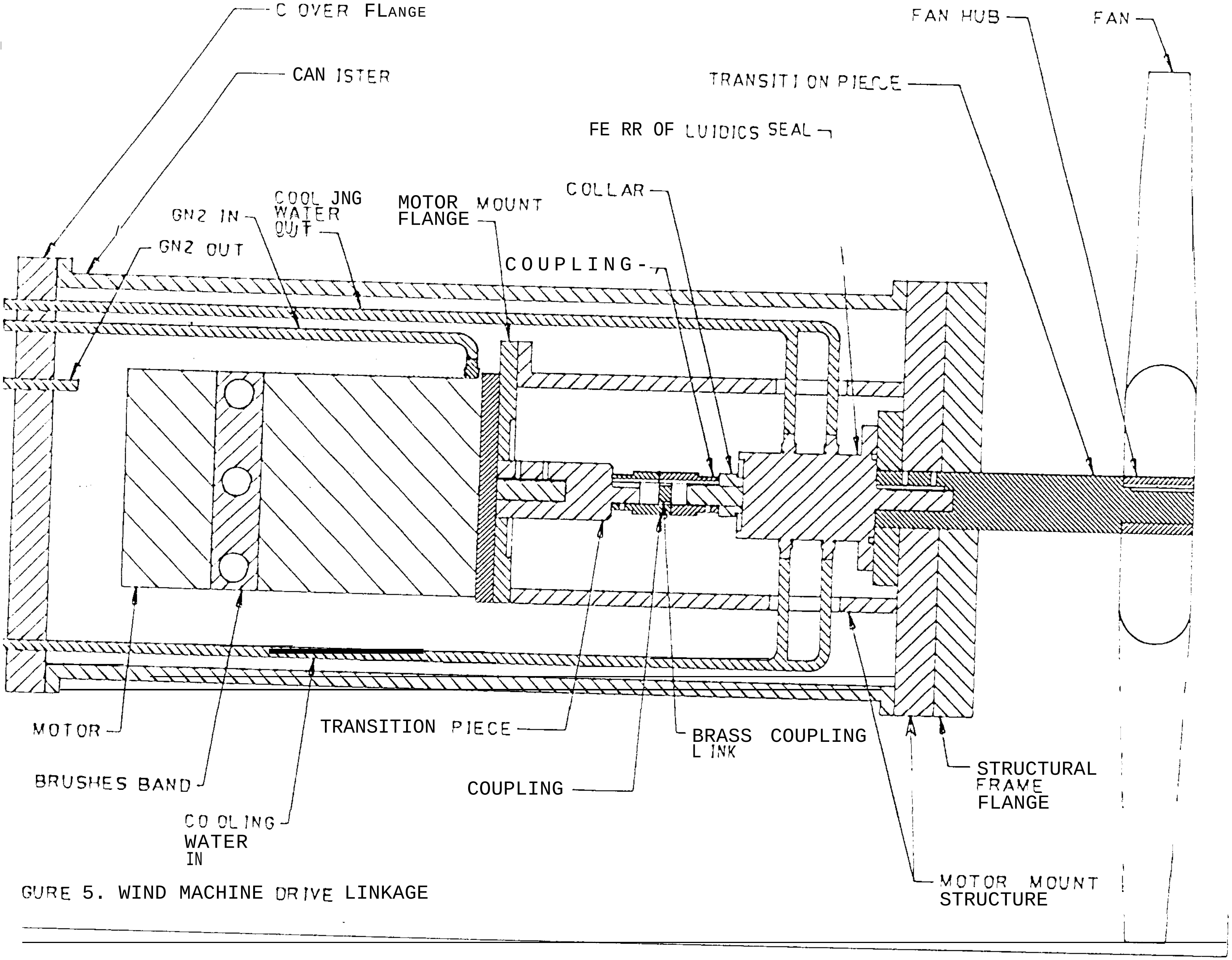


Figure 4. Photograph of Mars Rover Test Set-up



GURE 5. WIND MACHINE DRIVE LINKAGE

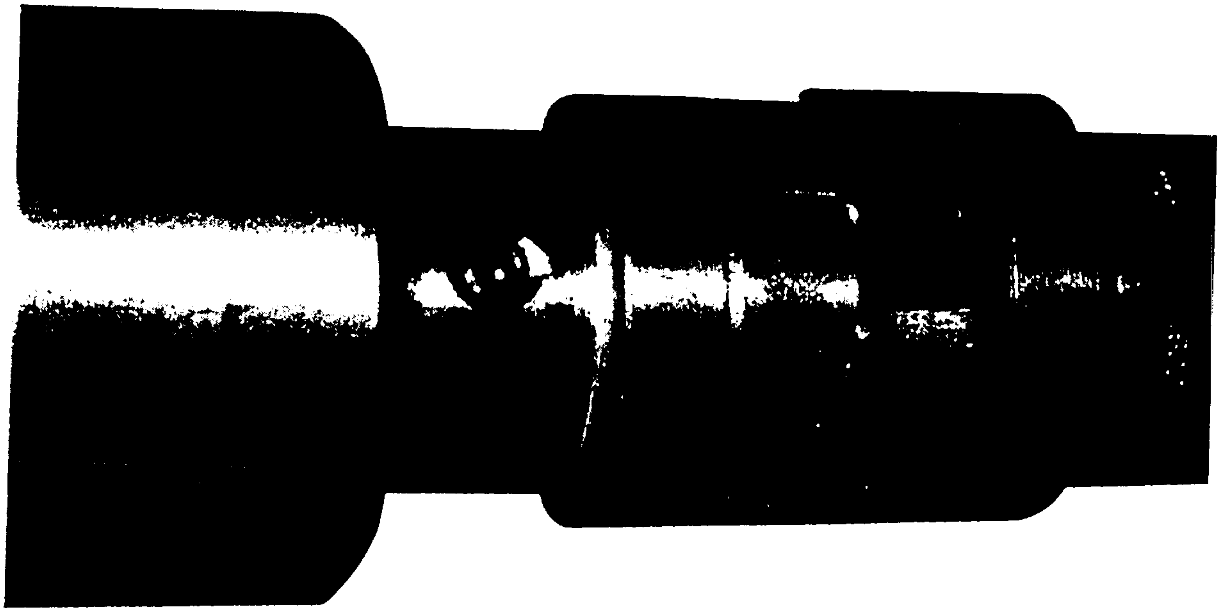
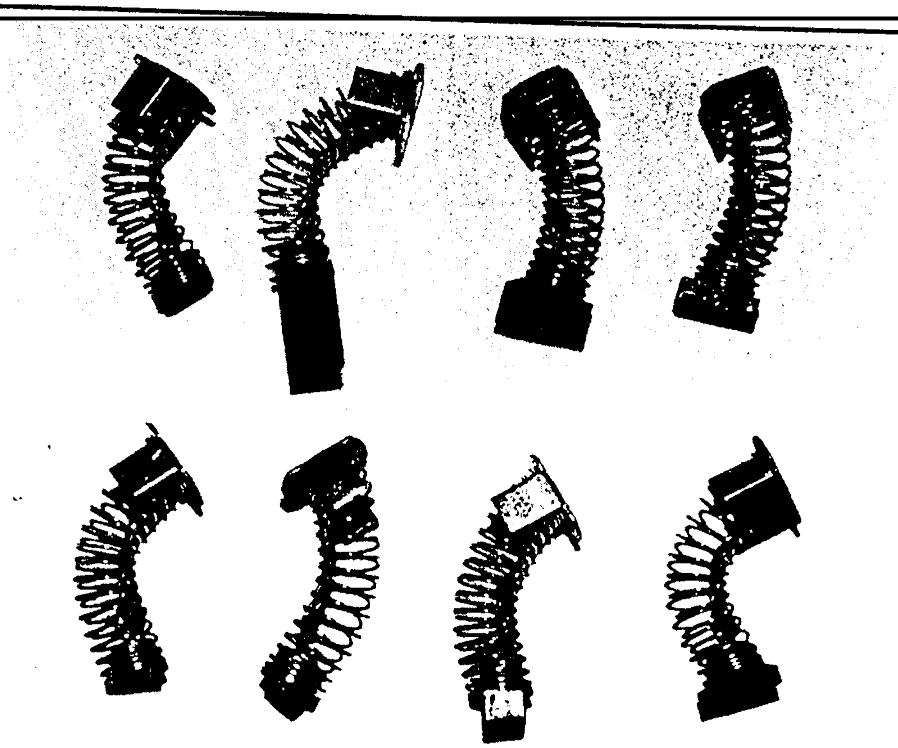


Figure 6. Photograph Showing the Coupling Separation



;ure 7. Photograph Showing Worn Carbon Brushes

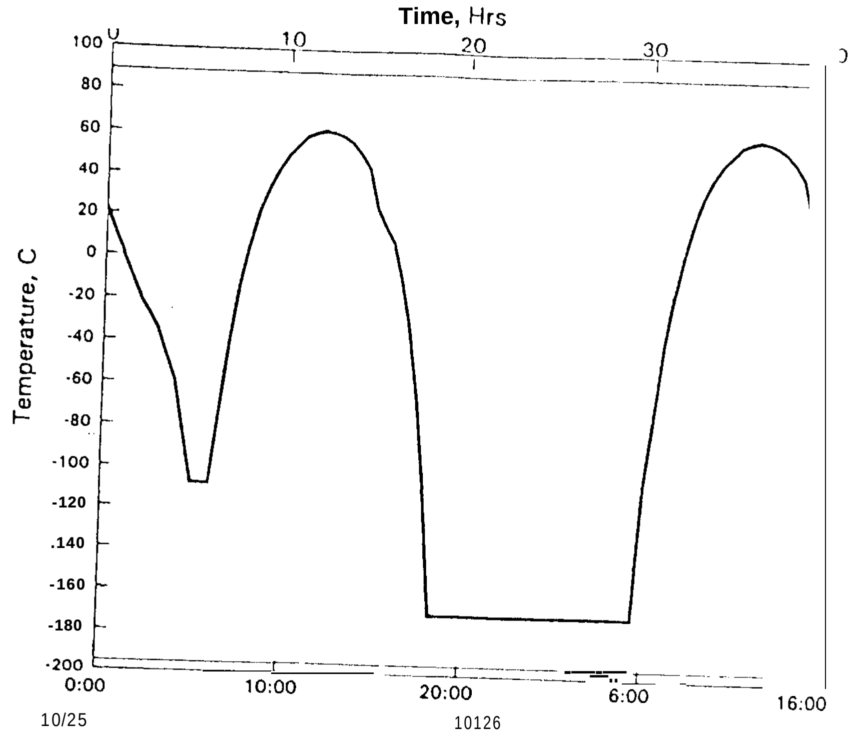


Figure 8a. Prescribed Sky Plate Temperature Profile for SIM-Q2a

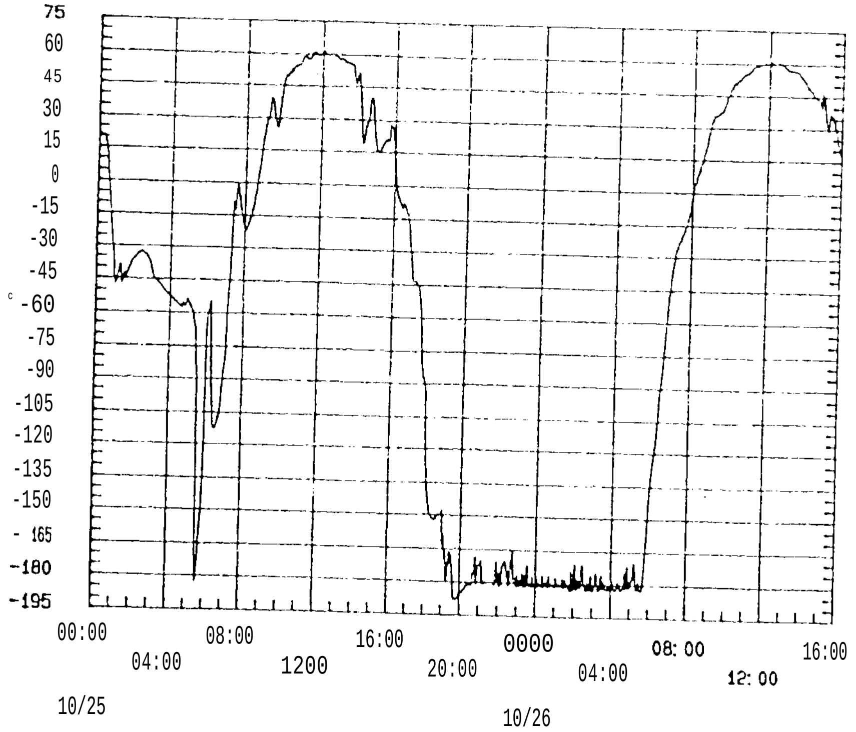


Figure 8b. Measured Sky Plate Temperature Profile for SIM-Q2a

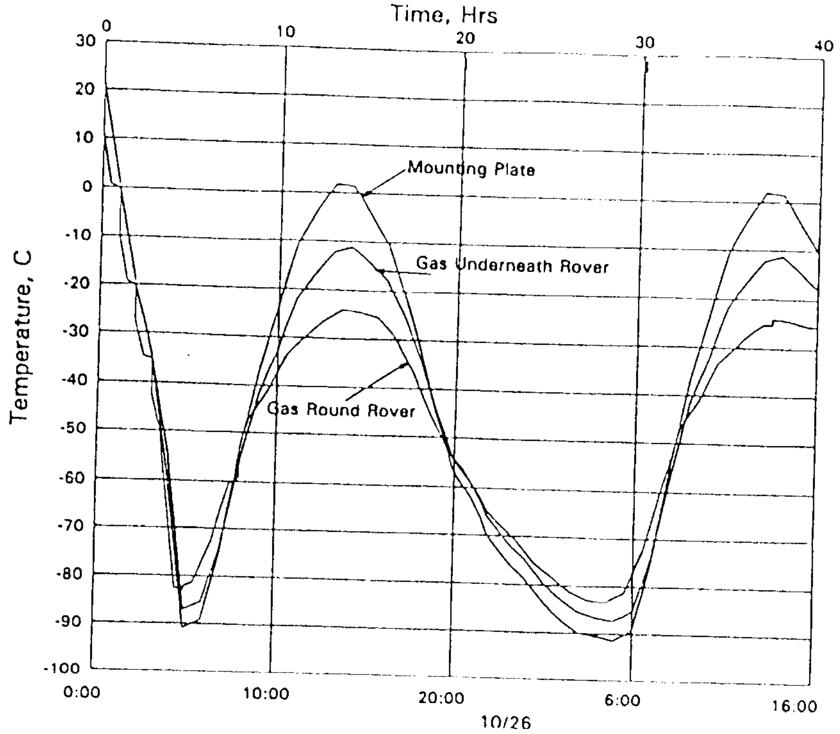


Figure 9a. Prescribed Mars Environmental Temperature Profiles for SIM-Q2a

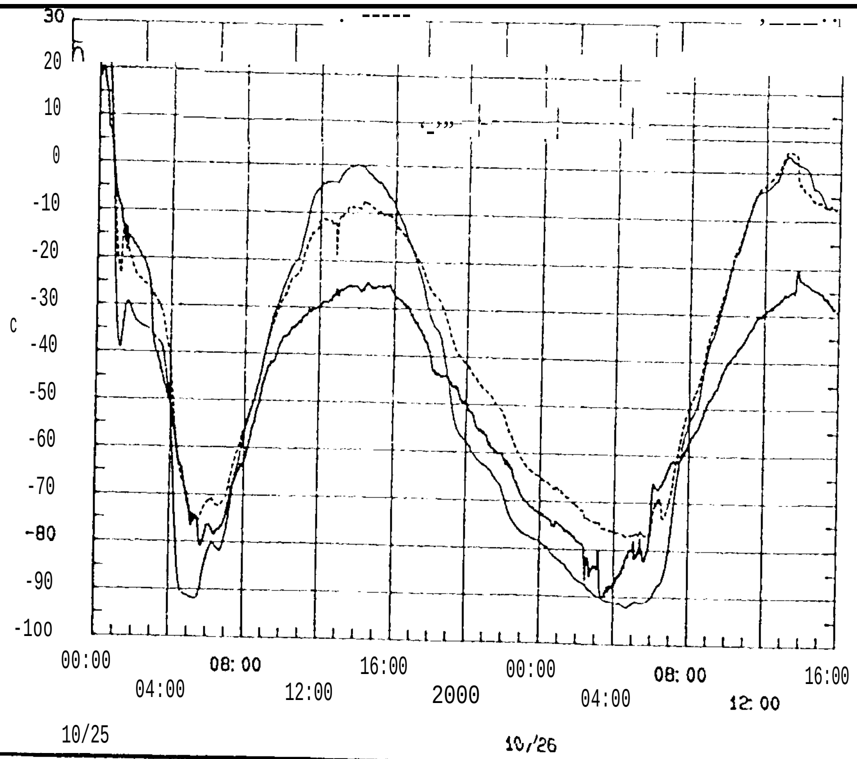


Figure9b. Measured Mars Environmental Temperature Profiles for SIM-Q2a

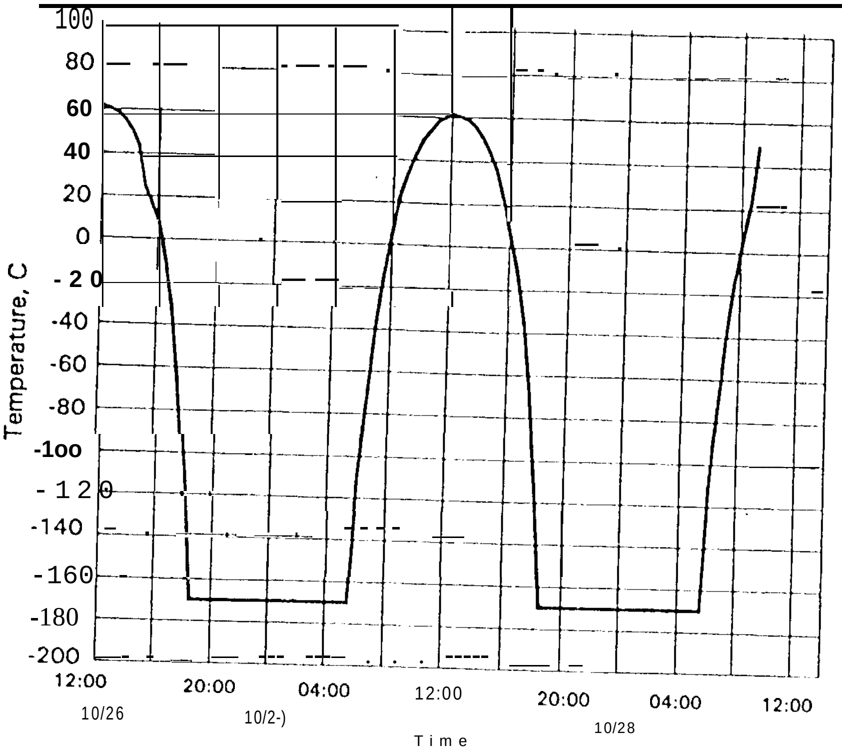


Figure10a. Prescribed Sky Plate Temperature Profile for SIM-Q2b

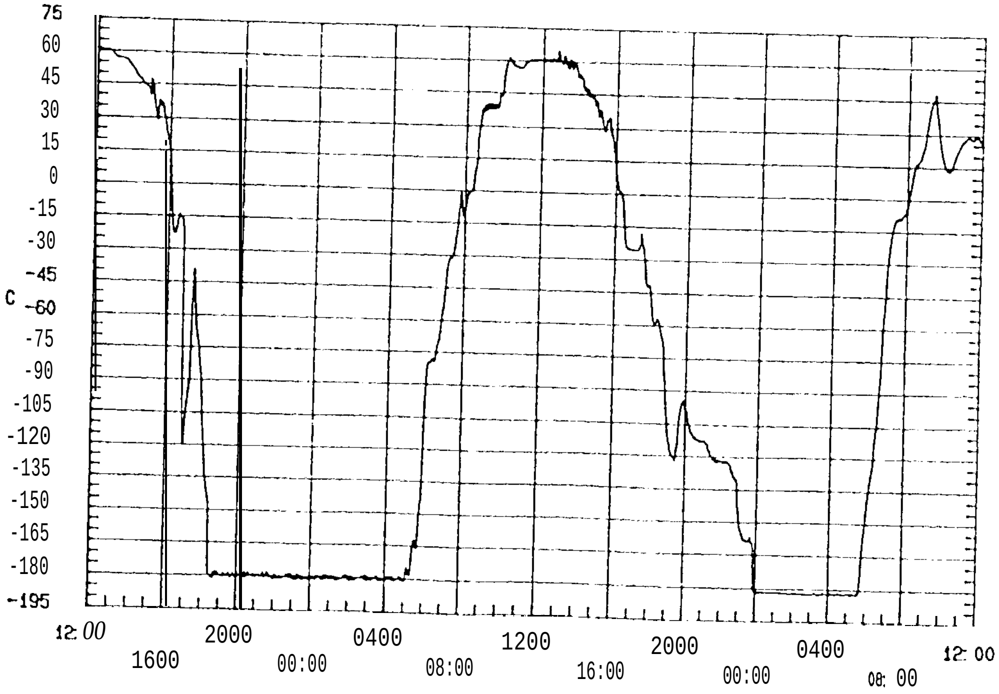


Figure10b. Measured Sky Plate Temperature Profile for SIM-Q2b

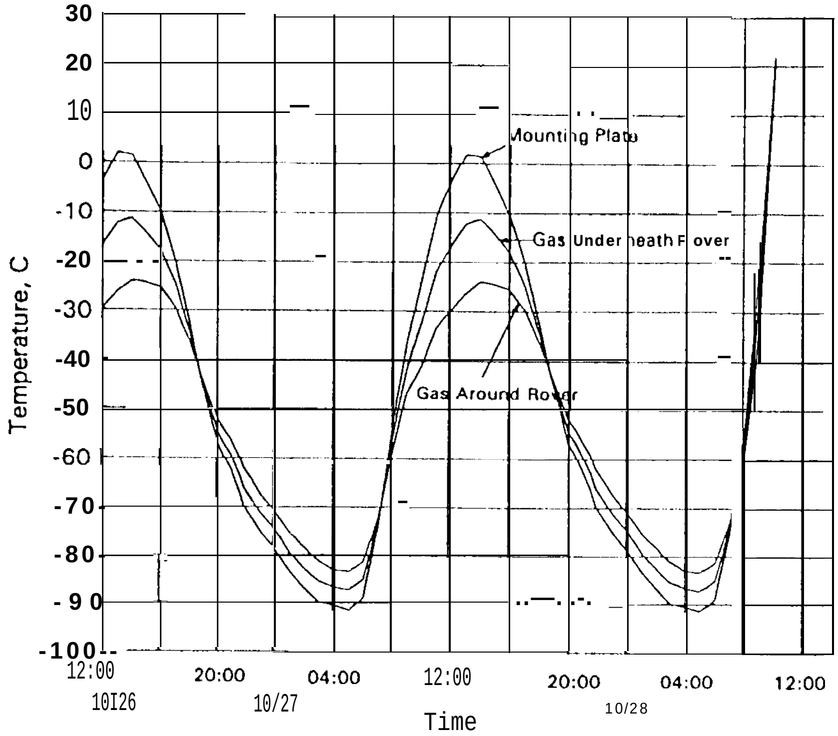


Figure1 la. Prescribed Mars Environmental Temperature Profiles for SIM-Q2b

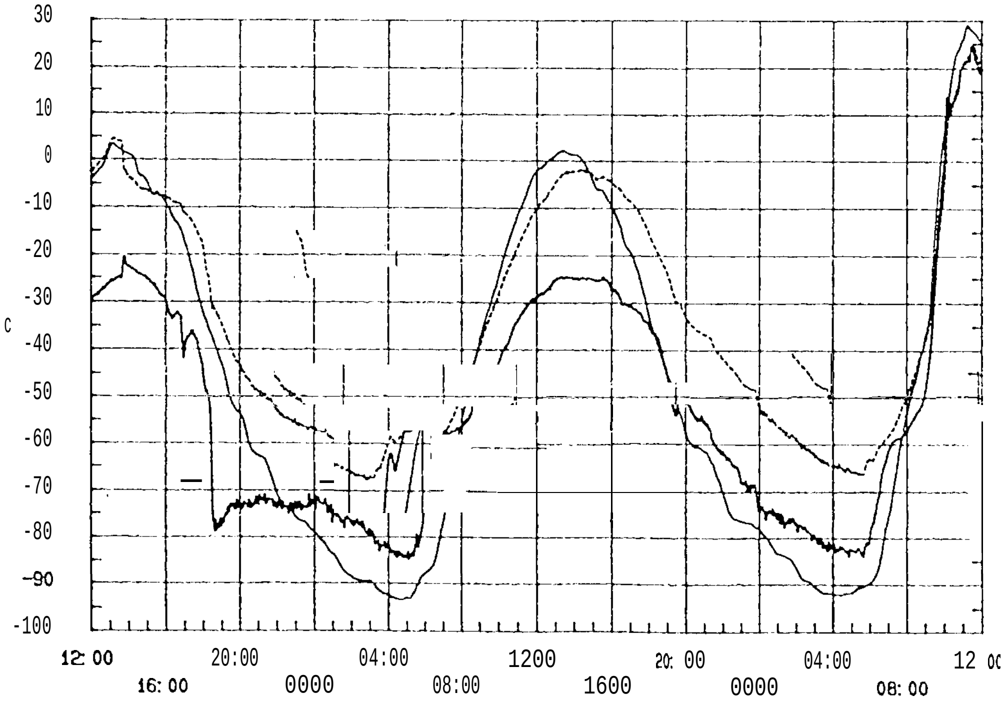


Figure1 lb. Measured Mars Environmental Temperature Profiles, for SIM-Q2b