MARS PATHFINDER SPACECRAFT, LANDER, AND ROVER TESTING IN SIMULATED DEEP SPACE AND MARS SURFACE ENVIRONMENTS

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ABSTRACT

The Mars Pathfinder (MPF) Spacecraft was built and tested at the Jet Propulsion Laboratory during 1995/96. MPF is scheduled to launch in December 1996 and to land on Mars on July 4, 1997. The testing program for MPF required subjecting the mission hardware to both deep space and Mars surface conditions. A series of tests were devised and conducted from 1/95 to 7/96 to study the thermal response of the MPF spacecraft to the environmental conditions in which it will be exposed during the cruise phase (on the way to Mars) and the lander phase (landed on Mars) of the mission. Also, several tests were conducted to study the thermal characteristics of the Mars rover, Sojourner, under Mars surface environmental conditions. For these tests, several special test fixtures and methods were devised to simulate the required environmental conditions. Creating simulated Mars surface conditions was a challenging undertaking since Mars' surface is subjected to diurnal cycling between -20°C and -85°C, with windspeeds to 20 m/sec, occurring in an 8 torr CO_2 atmosphere. This paper describes the MPF test program which was conducted at JPL to verify the MPF thermal design.

INTRODUCTION

The Mars Pathfinder spacecraft consists of a cruise stage (Fig. 1), a lander stage (Fig. 2) and a rover which is housed within the lander stage. A circular solar panel shades and powers the cruise stage as it travels to Mars, keeping the communications alive, the lander warm, and the batteries charged. When the spacecraft approaches Mars, the cruise stage will be jettisoned and the lander module will be propelled to enter the Mars atmosphere. The lander will descend towards the Mars surface, protected by a heat shield as it aerobrakes through the atmosphere. A 12.7 m diameter parachute (Dacron canopy with Kevlar suspension lines) will deploy at 10 km above the surface (Fig. 3). When the lander has descended to within 70 m of the surface, retro-rockets will fire to further slow the lander. Then, just before landing, a four-pod airbag made of Vectran will deploy to cushion the impact of the lander at touchdown (Fig. 4). The airbag encased lander will bounce several times before coming to rest on the Mars surface. Once settled on the surface, the airbags will be deflated and then, over a 1.7 hr period, will be retracted towards the lander using a cable-reeling winch system.

The lander in its stowed configuration is a tetrahedron which has three side "petals" surfaced with solar panels and a base petal on which the lander instruments are mounted. Once the airbag has retracted, three drive motors will slowly open the petals and, as the petals open, the lander will right itself so that the base petal will rest on the Martian surface with the side petal solar panels facing upward. The retracted Vectran airbag material will serve to cushion the petals as they open and insulate them from the cold Martian ground. Once the petals are open, the lander and the rover will be fully exposed to the Martian environment. During the first day on Mars, the solar panels will recharge the landers batteries. Also on the first day, the rover (Fig. 5) will be commanded by remote control operators on Earth to drive down a ramp from its mount on one of the petals and onto the Mars surface to begin its exploratory adventure (Fig. 6).

The Mars Pathfinder lander includes a weather station to provide metrology of the Mars surface temperature and pressure, a video camera system, and a rover. The rover will be equipped with aft and fore cameras for Mars surface surveillance, a laser-based autonomous navigation system for obstacle detection and avoidance, an Alpha-Proton X-Ray Spectrometer (APXS), and a communications system.

The testing program described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

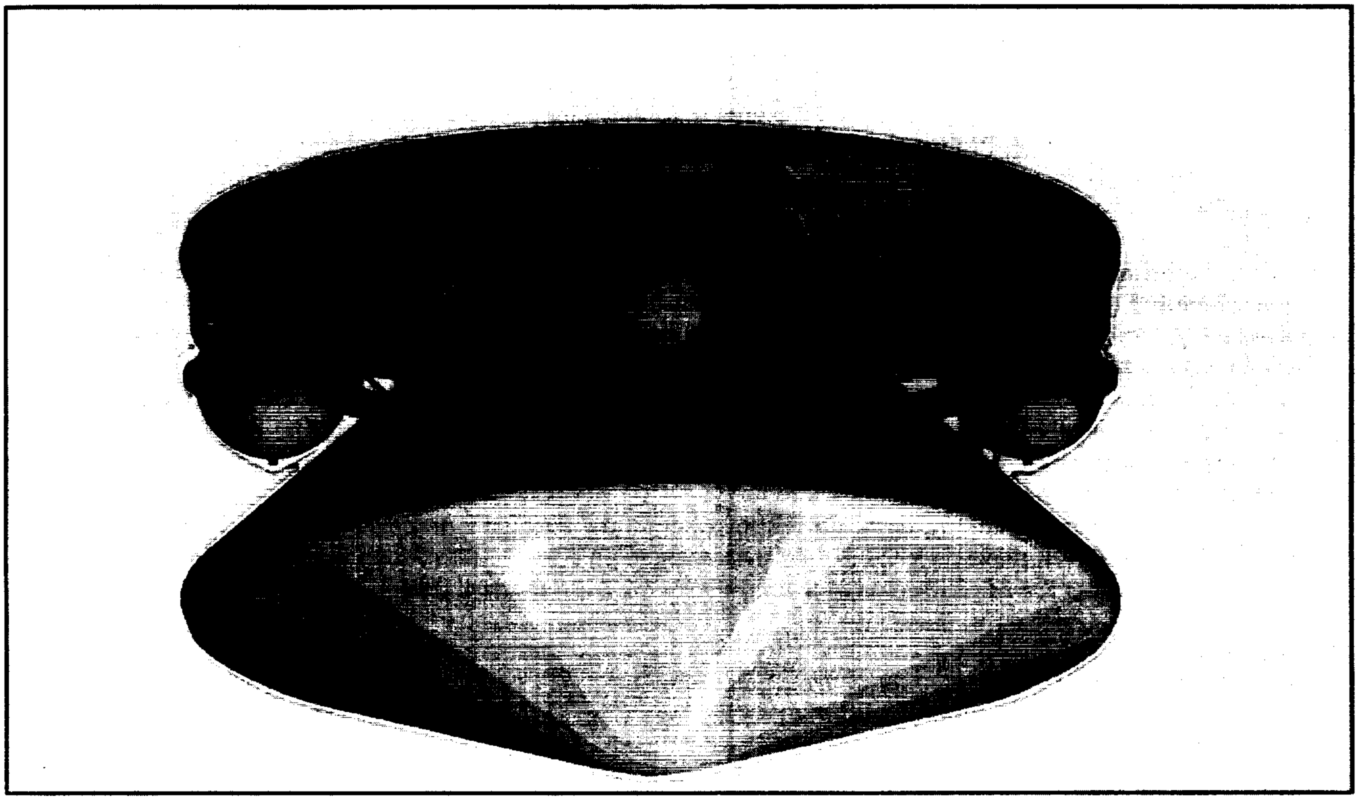


Figure 1. Mars Pathfinder Cruise Configuration

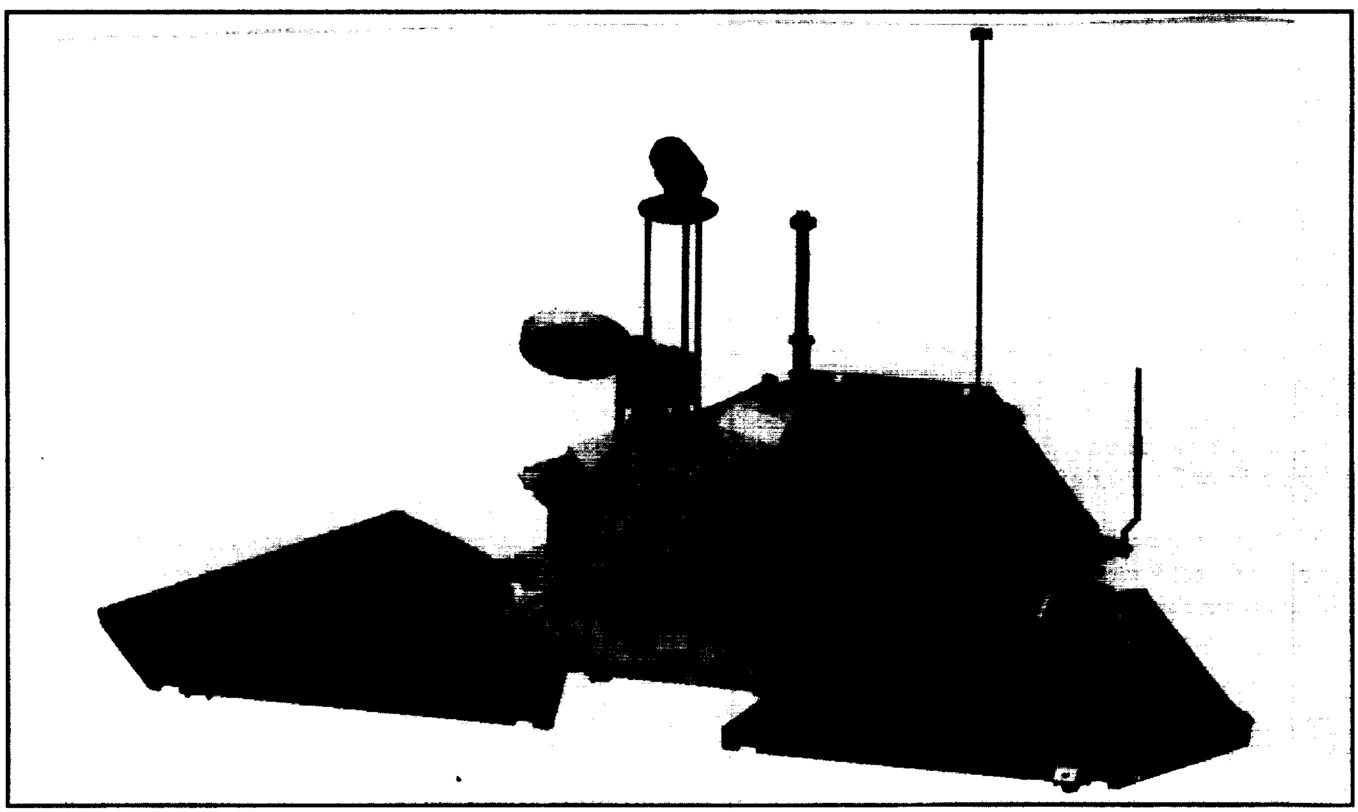


Figure 2. Mars Pathfinder Lander Configuration

Figure 3. Descent of the Mars Pathfinder Lander

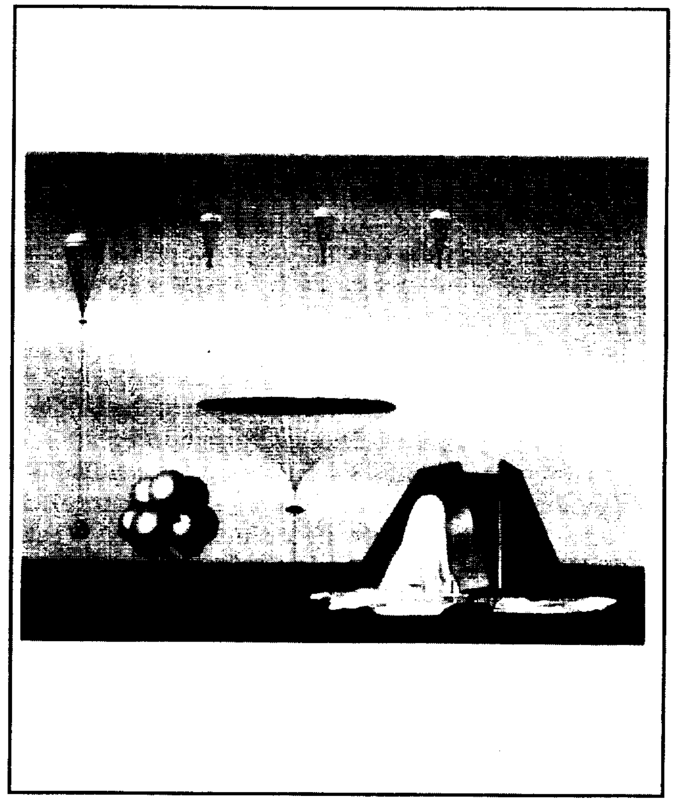


Figure 4. Mars Pathfinder Landing on Mars

Figure 5. Deployment of the Instrumentation and Rover

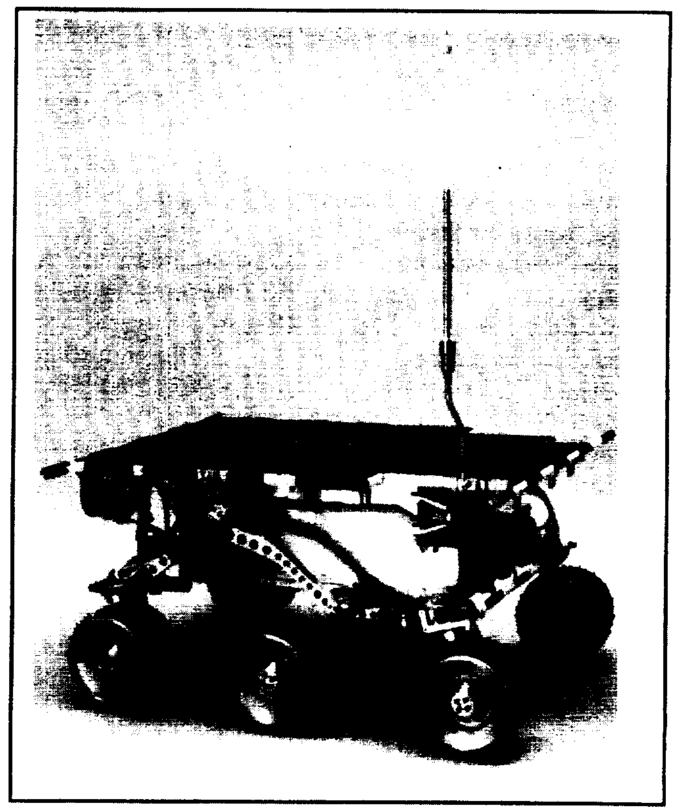


Figure 6. Close-up Photograph of the Mars Rover

The MPF test program included:

1) a test to understand the nuances of creating an 8 torr CO2 environment in a vacuum chamber for the purpose of creating as real a simulation of the Martian atmosphere as possible;
2) a test to study the thermal response of Mechanical, Thermal and Mobility (MTM) subsystems of a rover test model in cruise and landed phase conditions (this test also compared the thermal response of the rover test model in a CO2 environment against that in a GN2 environment at the same temperature and pressure conditions);
3) a test to study the thermal response of MTM subsystems of the rover test model to Mars surface conditions including wind and to verify the operation of a wind producing test assembly for use in a cold, 8 torr GN2 environment;
4) a test to study the thermal response and operational functionality of the insulated structural assembly and the heat rejection system (ISA/HRS) in the cruise environment;
5) a test to study the thermal response of the lander assembly in a Mars surface environment;
6) a test on a rover flight level System Integration Module (SIM) to verify the rover's thermal design as well as its communications software and functionality of some of the hardware ;
7) an airbag retraction test in a simulated Mars environment (cancelled because of airbag contamination);
8) a bakeout of the 25-ft space simulator (SS) to establish a baseline chamber cleanliness measurement;
9) a bakeout of a sun shade for installation in the 25-ft SS to be used to shade the infrared lamp support structure to be used for conducting the MPF-STV-1 test;
10) a proof-of-concept test of the 25-ft SS with no installed hardware to verify that the facility could safely provide the test conditions for the MPF lander full assembly solar thermal vacuum test (MPF-STV-2);
11) a test of the full MPF cruise stage assembly in a simulated deep space environment to study the thermal response of the entire spacecraft in near Earth, cruise, and near Mars conditions (MPF-STV-1); and
12) a test of the full MPF lander stage assembly, deployed in the landed, airbag-retracted configuration, in a simulated Mars environment to study the thermal response of the lander on the first and subsequent day on Mars, and to study the full functionality of the rover in a simulated Mars environment (MPF-STV-2).

In this paper, I will describe some of the more important aspects of these tests including discussions of special fixtures that were developed to create the required test conditions, and some of the results of the test program.

CREATING AN 8 TORR CO2 ENVIRONMENT IN A VACUUM CHAMBER (1)

The MPF thermal engineers started the MPF thermal test program assuming that the simulation of the Mars environment would be done using CO2 at 8 torr throughout the entire test program. This assumption was based on the desire to test in the most realistic simulation of the Mars environemtn that was possible. The first hardware subassembly test in CO2 was conducted in one of JPL's small chambers, 3-ft diameter and 5-ft long, in January 1995. For this test, the operating technicians used a standard vacuum chamber procedure which included the use of an LN2 flooded cold finger to collect outgassed contamination from the hardware. After the normal initial pumpdown of the chamber and the chilling of the cold finger with LN2, the operators introduced CO2 into the chamber to a pressure level of 8 torr.

However, operators soon noticed that the chamber pressure could not be held at 8 torr without a constant feed of CO2 into the chamber. Before anyone discovered the reason why the pressure could not be stabilized at 8 torr, a loud clunk was heard coming from inside the chamber. This prompted the operators to rapidly return the chamber to atmospheric pressure to inspect the hardware. A large block of frozen CO2 (dry ice) was found which had been formed on the cold finger inside the chamber. The block had broken off the cold finger and dropped to the floor of the chamber. A brief review of the solid-gas equilibrium data for CO2 revealed that CO2 at 8 torr solidifies at -121℃. It was clear that a standard LN2 cold finger could not be chilled below about -115℃ and that maintaining an 8 torr CO2 pressure in the vacuum chambers would be difficult to achieve. Therefore, the use of GN2 was recommended as an alternative to CO2 for subsequent Mars surface environment simulations.

ROVER MTM TESTING (2)

The rover MTM testing was conducted in JPL's Chamber 10 from 4/20 to 5/5/95. This test was the first of the MPF test series to simulate the cruise stage as well as the first day on Mars conditions and several subsequent diurnal temperature cycles. A primary thermal design goal of the rover thermal engineers was to ensure that the Warm Equipment Box (WEB) was insulated with aerogel well enough that the WEB inside the rover would never get colder than -40°C even when subjected to external temperatures as low as -85°C, the projected night time low temperature of the Martian surface atmosphere. Martian surface environment simulation included the use of CO_2 at 8 torr for most of the various MTM tests. A test was conducted using GN_2 at 8 torr to compare the thermal effects between CO_2 and GN_2 environments. As part of the test set-up for the MTM tests, two aluminum reference plates with Minco film heaters were mounted inside the chamber, one surfaced with a Cat-a-lac black paint (emittance 0.87) and one surfaced with gold-coated kapton (emittance 0.06), to provide a method for calibrating the heat transfer characteristics. The black reference plate was used primarily for calibration during high vacuum operations where thermal radiation is the main mode of heat transfer. The gold reference plate, which because of its low emissivity, was used during the 8 torr operations to measure the convective heat transfer effects while minimizing the radiative heat transfer effects.

Thermal engineers L. Wen and E. Kwack planned this test. The results of this test were reported by L. Wen (ref. 1). Wen states that the free convective heat transfer coefficient on the rover surface may be 28% to 35% higher in a GN_2 environment than in a CO_2 environment (ref. 2). The test data indicated that rover internal components can be expected to get 3.5°C to 4°C colder in a GN_2 environment than they would in a CO_2 environment (ref. 3). Because of the technical difficulty and considerable expense of using CO_2 in the thermal vacuum chambers to create a realistic Mars environement, it was decided that GN_2 be used in place of CO_2 for simulating Mars surface environmental conditions on all subsequent tests.

This test also indicated that there were significant thermal effects introduced to the rover by the free convection currents created by the temperature differentials between the chamber wall shrouds and the temperature-controlled heat exchanger panel on which the rover EM was mounted (Fig. 7). It was suggested that the next test, which would introduce wind and thus induce some forced convection, would help clarify and quantify the significance of these effects.

ROVER MTM TESTING IN THE PRESENCE OF WIND (3)

The next step was to test the rover model in a simulated Mars environment with wind blowing at various speeds to study the effect of wind on the heat transfer from the WEB and other rover components. This test was called the Rover EM Wind Test, was planned by thermal engineers L. Wen and E. Kwack, and was conducted in JPL's 10-ft SS on 6/25-30/95. A special wind-generating fixture was fabricated to blow a wind stream across the rover EM at various wind-speeds (Fig. 8). L. Wen's report on this test (ref. 4) states that the test results indicate that the forced convection heat transfer coefficient due to wind was double that of the free convection heat transfer coefficient when there is no wind. The rover interior temperature was measured to be about 4°C lower with wind than without.

In addition to simulating windspeed, an overhead skyplate heat exchanger (HX) was installed to simulate the diurnal sky temperature in both day time and night time conditions. Also, a compensator HX was mounted above the skyplate to provide trim temperature control of the circulating GN_2. A mylar baffle canopy mounted directly above the compensator HX kept the circulating GN_2 confined to a relatively limited volume around the test fixture and the test article. Operators had some trouble achieving a smooth diurnal temperature cycle since the temperature control of the wall and floor shrouds (which provided the background Mars surface temperature) lagged and sometimes counteracted the temperature control of the skyplate and the compensator. However, the results of this test provided the thermal engineers with enough empirical data to conclude with some confidence that the rover thermal design would be effective in keeping the rover interior components above -40°C under actual Mars surface diurnal conditions.

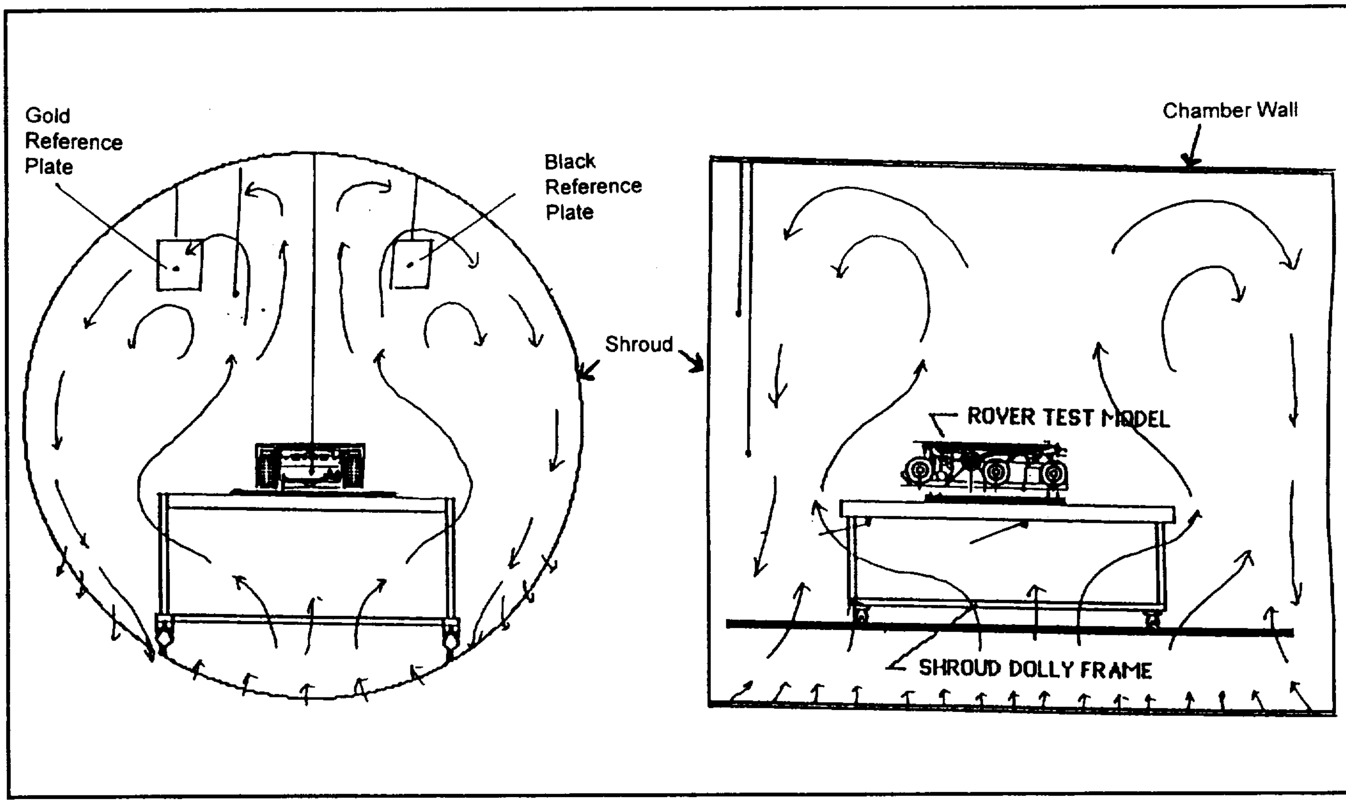


Figure 7. Free Convection Around the Mars Rover Test Model in JPL's Chamber 10

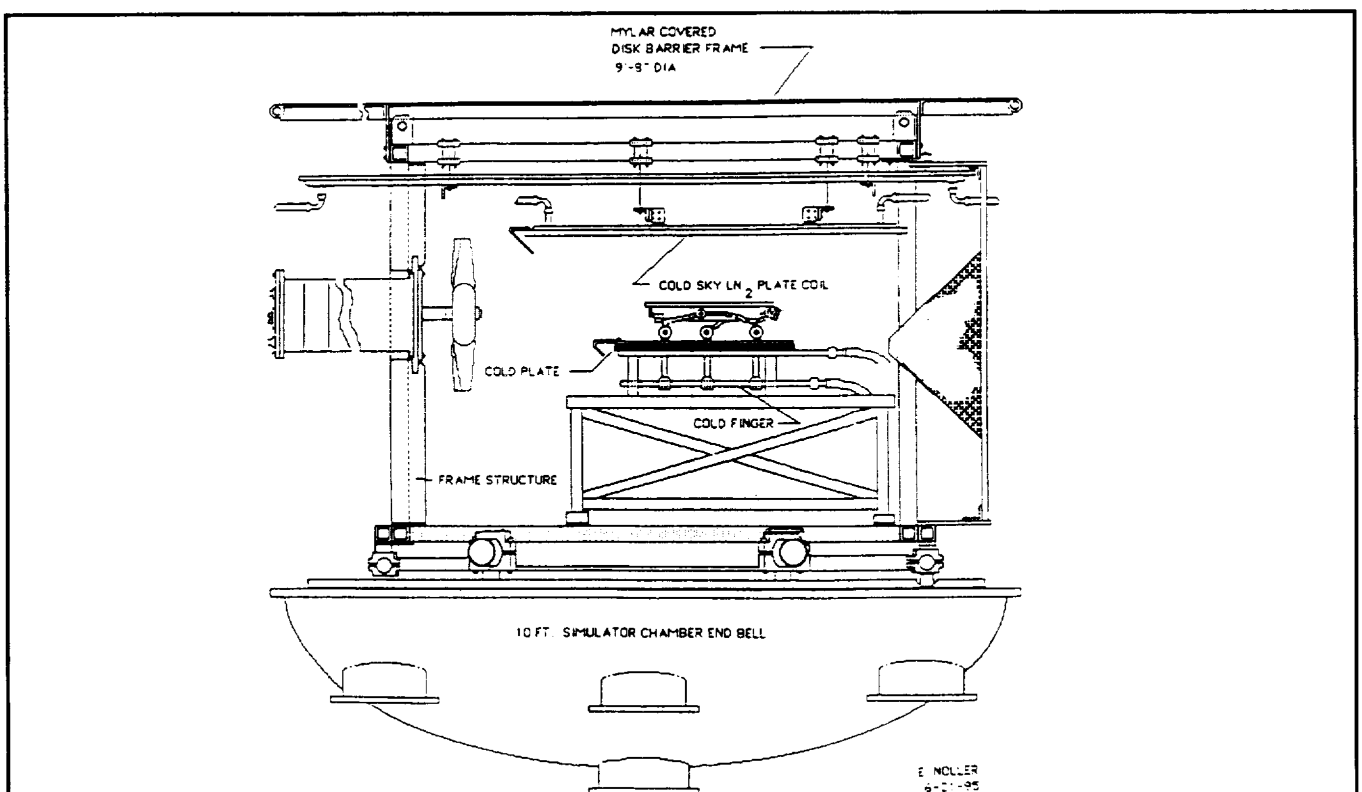


Figure 8. Test Set-up for the Mars Rover MTM and SIM QUAL Tests Including the Wind Machine Configuration

CRUISE PHASE TESTING OF THE MPF ISA/HRS (4)

The thermal control design of the MPF flight system design required most of the electronics to be used in both the cruise and Mars surface operations. To meet this requirement, the heat rejection system (HRS) was designed to dissipate the heat generated by the electronics during the cruise stage. The insulated structural assembly (ISA) was built to minimize the equipment heat loss during Mars surface operations. The HRS is a pumped closed-loop, single phase cooling system using Freon 11 as the circulating fluid (Fig. 9). Freon is warmed as it flows through the ISA electronics box. Part of the warmed freon stream is cooled as it flows through a radiator partially exposed to space while the remaining part of the warmed freon stream is by-passed around the radiator and is mixed with the cooled part to provide a temperature-controlled freon stream back to the ISA. The ISA houses the major electronics and telecommunications equipment and helps in controlling their temperatures within the general range of -40°C to +40°C during Martian surface operations. The ISA is a thermally insulated enclosure made of an Eccofoam layer and a Nomex honeycomb structural layer filled with crushed Eccofoam material. The ISA surface is coated with Cat-a-lac white paint.

The MPF ISA/HRS cruise phase thermal characterization test was planned by thermal engineers J. Lyra, K. Novak, and H. Awaya and was conducted in JPL's 10-ft SS on 8/19-26/95. The test objectives were: 1) to validate the lander/ISA/HRS integrated thermal design in the worst case cold and hot cruise conditions; 2) to determine the sensitivity of the lander/ISA/HRS to the MPF backshell temperature (since the backshell is the main boundary of the lander/ISA/HRS) in both worst case cold and hot conditions; 3) to assess the impact of an HRS failure during cruise (results used to develop a contingency plan in case of an HRS failure during flight); 4) to validate the thermal design and heater sizes of basepetal mounted equipment in a simulated Mars entry environment with emphasis on the lander petal accuator (LPA) and its electronics box, the airbag retraction actuator (ARA) and the gas generators (GG); and 5) to characterize the warmup rate of the ISA electronics after the HRS has been turned off.

The ISA/HRS cruise phase test configuration is illustrated in Figure 10. The lander in the stowed configuration was suspended above a blanket of multi-layer insulation laid on top of a heat exchanger (HX) plate which was temperature-controlled to simulate the cruise stage heatshield. The lander was hung from three cables attached to hard points on the inside chamber wall. The chamber wall shrouds were used to simulate the MPF backshell temperature. Figure 11 shows details of the HRS simulation test set-up. Figure 12 is a photograph which shows the test set-up just prior to hanging the test article in the chamber.

A method for accelerated chilling of the test article was provided to achieve cruise steady state temperature conditions as quickly as possible. A 0.25-in stainless steel tube was plumbed to feed LN2 directly into the chamber below the test article. When LN2 discharges into the chamber, it exits the tube as solid nitrogen pellets about 0.125-in in diameter. These small pellets evaporate rapidly to provide quick localized cooling. After first roughing the chamber to about 1×10^{-2} torr, backfilling once with GN2 to 400 torr to flush residual water vapor, re-roughing to about 1×10^{-2} torr, flooding the contamination plate with LN2, then chilling and LN2 flooding both the chamber wall shrouds and the heatshield HX, LN2 was fed into the chamber until the pressure reached 100 torr. When the temperature of the spacecraft side and base petals reached $\leq$ -50°C, the LN2 was drained from the shrouds and the HX, the shrouds and HX were warmed to -95°C and -145°C, resp., then the chamber was evacuated by normal procedure to $\leq 1 \times 10^{-5}$ torr to start the cruise phase test.

Results of this test were reported by J. Lyra/K. Novak/H. Awaya (ref. 5). In general, the test demonstrated that safe margins of at least 20°C will exist for all lander components in both the hot and cold conditions during the cruise phase.

LANDER PHASE TESTING OF THE MPF ISA/HRS (5)

The MPF ISA/HRS lander phase thermal characterization test was planned by thermal engineers J. Lyra, K. Novak, Y.C. Wu and H. Awaya and was conducted in JPL's 10-ft SS on 9/5-15/95. The test objectives were: 1) to characterize the thermal performance of the ISA Eccofoam/Nomex honeycomb insulation on the Mars surface; 2) to gather data to validate the thermal math models; 3) to characterize the transient behavior of the ISA equipment during at least one Mars day; and 4) to characterize the transient response of the secondary battery.

The ISA/HRS lander phase test configuration is illustrated in Figure 13. A photograph of the test set-up is shown in Figure 14. The ISA was mounted on the basepetal of the lander, the ISA/basepetal assembly was mounted on a twice-folded airbag (to simulate six layers between the basepetal and the ground), and the ISA/basepetal/airbag assembly was mounted on a "ground" HX plate used to simulate the temperature of the Martian ground surface. Solar simulation during the diurnal temperature cycling was accomplished by controlling the chamber wall shroud temperature and by powering heaters mounted on the ISA surface. A mylar canopy was installed about 4 feet above the test article to minimize convective gas circulation inside the chamber. Hardware for a propellant line thermal test (a test piggy-backed on the lander phase test) was mounted above the canopy. Accelerated chilling of the test article was accomplished in the same way as described in the cruise phase discussion. Although there was some concern about the possibility of overcooling the chamber walls and the carbon steel stiffener-ring welds on the chamber's external surface, only sweating (and no frost) on the external surface of the chamber was observed.

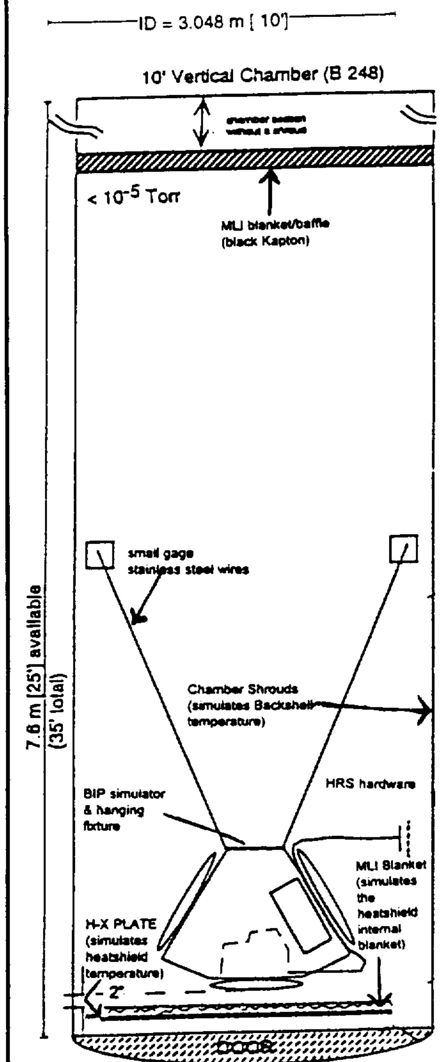
Results of this test were reported by J. Lyra/K. Novak/H. Awaya (ref. 6). Enough data was gathered to correlate the thermal math model in both radiation- and convection-dominated environments. Temperatures predicted by the math models correlated well with measured values, except for the ISA internal temperature which stayed considerably warmer than the model predicted.

MARS ROVER SYSTEM INTEGRATION MODULE (SIM) QUALIFICATION (QUAL) TEST (6)

The Mars rover SIM QUAL Test, was conducted in JPL's 10-ft SS on 10/23-28/95. This test emulated the rover MTM test in the presence of wind (3) described above. The test set-up was similar to the MTM test except that the test article now was a flight rover system integration module rather than a test model. The wind-generating machine was changed slightly to provide a forced stream of temperature-controlled GN2 directly into the motor housing to ensure that the motor would get adequate cooling. Also, a spare motor controller was brought to the test site to provide a back-up in case of a motor controller failure (which had occurred during the 6/95 test). Figure 15 shows a photograph of the test set-up. Figure 16 illustrates the details of the wind machine drive linkage.

This test was planned to occur in three phases: 1) <u>SIM-Q1:</u> calibration of the wind speed vs. motor rpm, followed by a steady state thermal vacuum test representing the cruise stage of the MPF spacecraft near Mars just before landing; 2) SIM-Q2a/b: with the rover stowed/unstowed, test the thermal response in nominal diurnal transient temperature conditions (at wind speeds of <u>≤ 6 m/sec)</u>; and, 3) SIM-Q3: with the rover stowed, test the thermal response in off-nominal diurnal transient temperature conditions (at wind speeds of > 6 m/sec).

The results of this test were reported by L. Wen (ref. 7), K. Johnson et al. (ref. 8), and G. S. Hickey et al. (ref. 9). During SIM-Q1, about two hours were expended performing the wind speed calibration but the measurements were unsteady and inconclusive. Because of a tight test schedule, we proceeded with the test plan without conclusive wind speed calibration data. It was decided to use the Cat-a-lac black and gold kapton coated aluminum reference plates for wind speed calibration. The reference plate wind speed calibration indicated that about 1 m/sec was achieved at a motor speed of 800 rpm. The wind-machine motor (a three-phase, 8-pole carbon brush, 5 hp dc motor) ran at about 800 rpm for four hours before it failed as a result of excessive wear of the carbon brushes as well as a disengagement of the coupling. The test was ended prematurely to find and fix the wind-machine problems. After replacing the brushes, increasing the line size of the motor-cooling GN2 line



HARDWARE

Lander
Petal Actuator (at least one)
DTM Air Bags (all)
DTM ISA
DTM equipment shelf (w/ cooling loops)
Gas Generator (1)
Air Bag Retraction Actuator (1)
Petal Actuator Electronics Box (1)
BIP simulator
cables
HRS support hardware

Thermal Development Models or
Engineering Models:

IEM	PSA or PSB
DST	Lander Thermal Battery
SSPA	Wave guide
AXT	Rover
TMU (2)	
CDU	
Battery	

Figure 10. ISA/HRS Cruise Phase Test Configuration

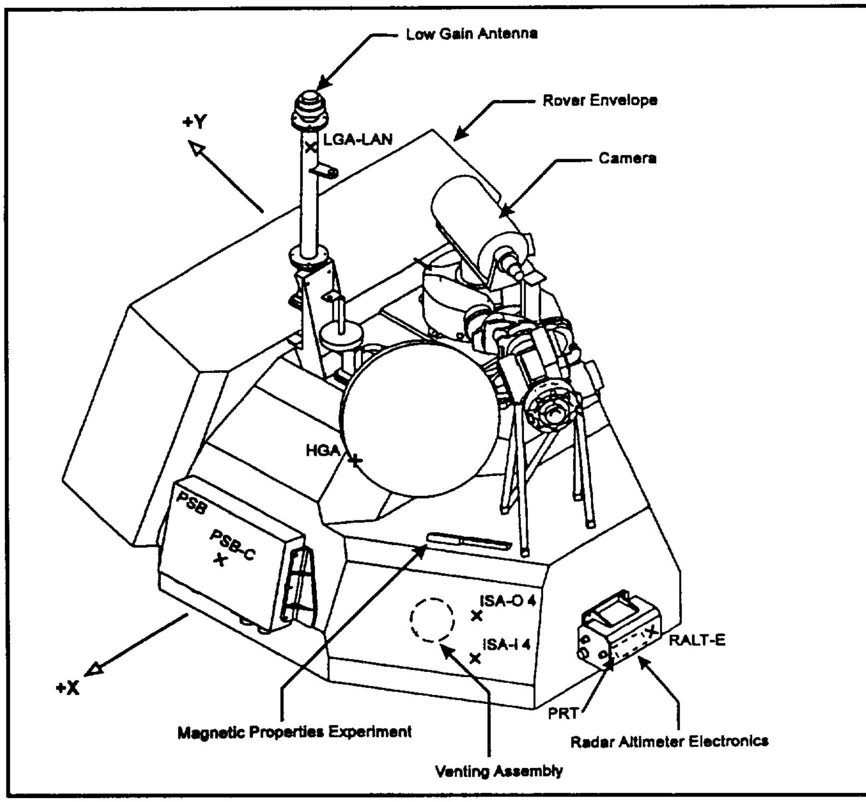


Figure 9. Lander and Insulated Structural Assembly Flight Cruise Configuration

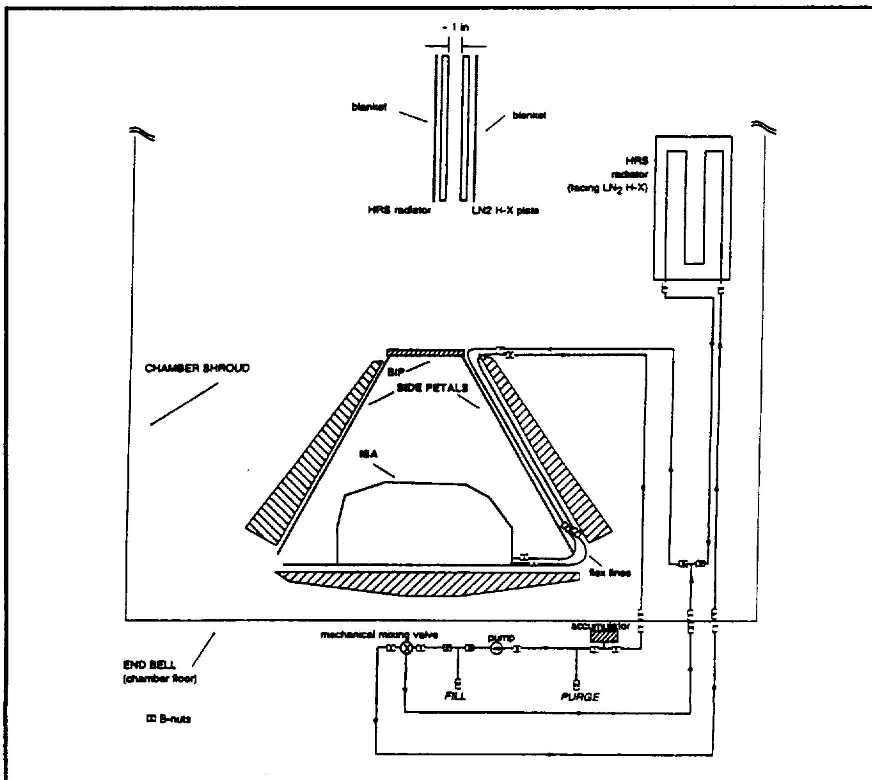


Figure 11. Details of the Test Set-up for the HRS Simulation Test

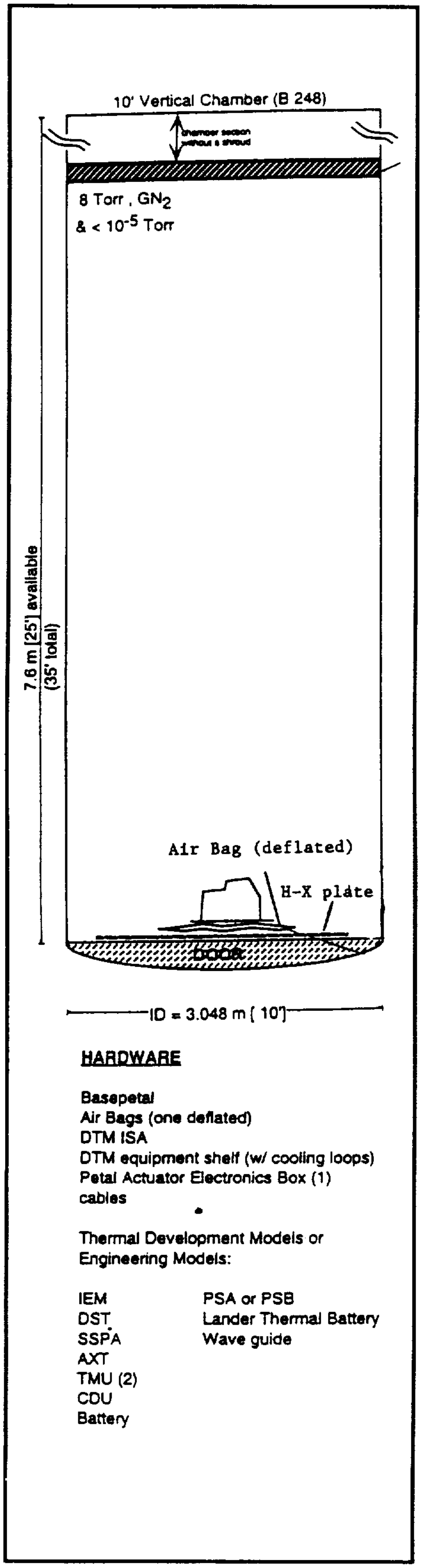


Figure 13. ISA/HRS Lander Phase Test Configuration

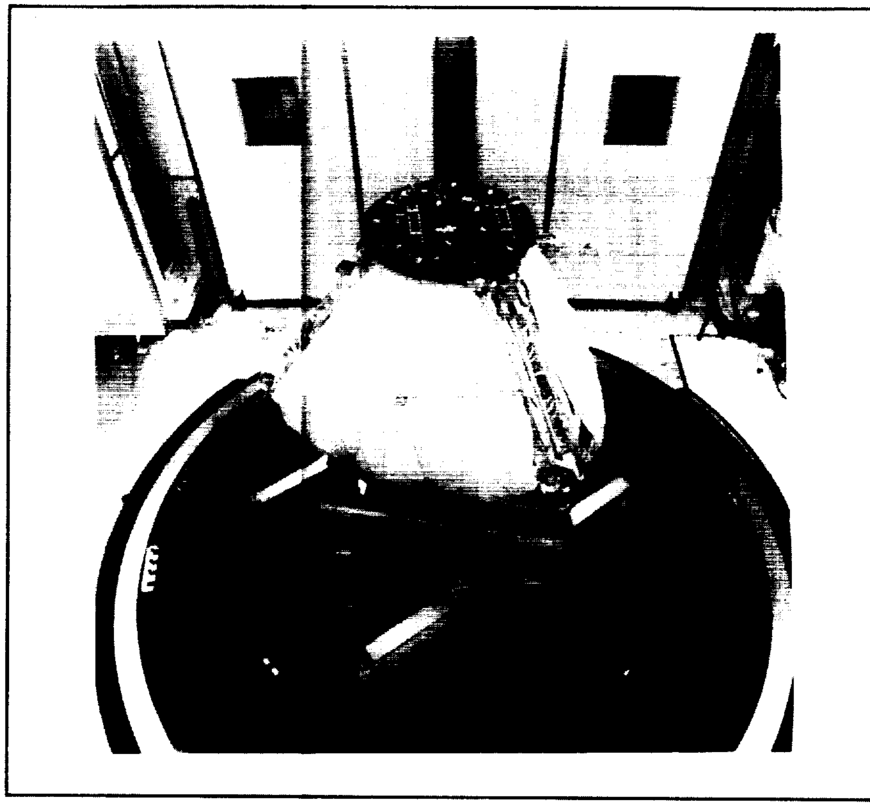


Figure 12. Photograph of the ISA/HRS Cruise Phase Test Set-up

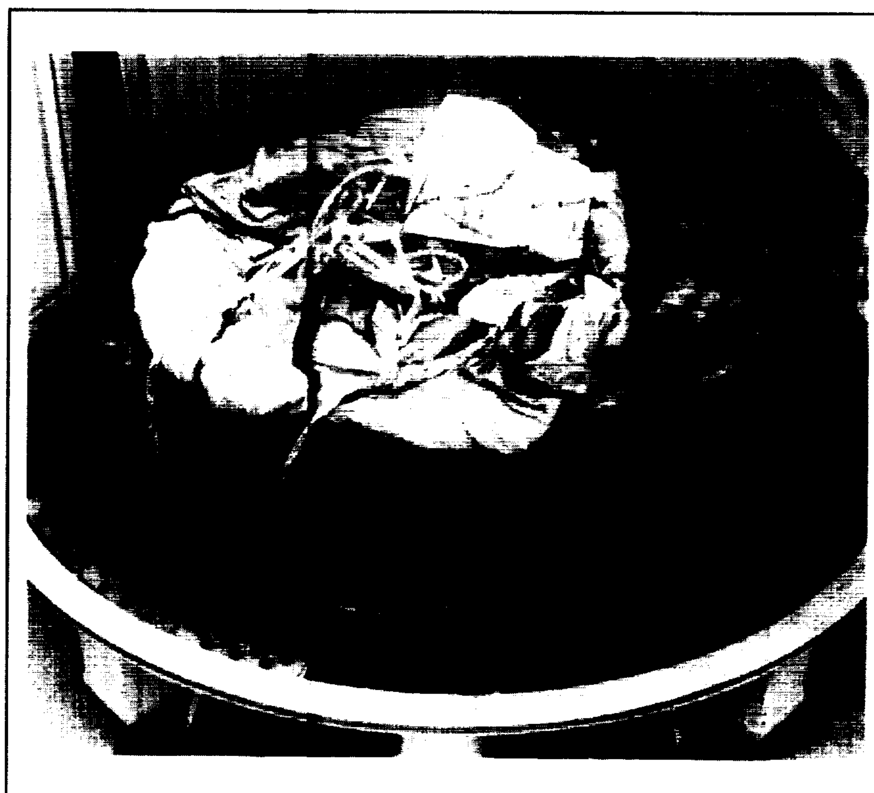


Figure 14. Photograph of the ISA/HRS Lander Phase Test Set-up

to hopefully improve motor cooling, and re-establishing and securing the coupling linkage, the test was restarted. This time the wind machine operated at about 800 rpm for about eighteen hours before it failed again. Post-test analysis of the motor and linkage showed that the failure was again caused by excessive wear on the carbon brushes and dis-engagement of the coupling linkage. The SIM-Q2a and b test phases were concluded but SIM-Q3 was cancelled because of the wind machine failure. Figure 17a shows the prescribed Mars environmental temperature profiles for SIM-Q2a and figure 17b shows the measured Mars environmental profiles which were created for SIM-Q2a.

Wen states in his report that although the failure of the wind generation system was a disappointing setback, the overall test objective was not severely impacted. The partial wind test data that was obtained, together with the thermal math model predictions based on previous tests, provides adequate confidence that the rover thermal design meets its performance expectations when subjected to a realistic transient test environment. This test accomplished its basic thermal objectives. No further work was done to improve the wind machine .

AIRBAG RETRACTION TEST IN A SIMULATED MARS ENVIRONMENT (7)

Plans were made to test the airbag retraction mechanism in a simulated Mars environment in the 25-ft SS in early December, 1995. The purpose of this test was to study the airbag retraction mechanism and to measure the effect the cold temperature would have on increasing the stiffness of the airbag over that measured in ambient Earth onditions. This increased stiffness increases the drag friction of the airbag on both the Mars surface and on itself as the airbag retracts. The purpose of this test was to verify that the retraction system would work properly in a Mars-like environment.

About two weeks before the test was to take place, the test conductor revealed that the test airbag was not a new airbag but one which had undergone a fired deployment test at NASA Lewis and was already contaminated inside with a soot like substance which was a by-product of the airbag deployment. An analysis of this substance revealed that it was primarily ammonium chloride salt with a significant quantity of carbon soot. Because of a very major concern that this material inside the bag would outgas significantly during the chamber evacuation and thus contaminate the chamber, a small portion of the material was tested in a small chamber to study its outgassing tendency. This test revealed that about 75 wt% of the material vaporized under vacuum conditions at ambient temperature. Therefore the airbag retraction test was cancelled.

BAKEOUT OF THE 25-FT SS TO ESTABLISH A CHAMBER CLEANLINESS BASELINE (8)

After completing the test campaign in the 10-ft SS, the facility operations staff redirected their attention to readying the 25-ft SS for the upcoming MPF solar thermal vacuum tests. This was to be the first spacecraft test in the 25-ft SS since completion of a major facility refurbishment. There were still some "bugs" in the facility systems that needed to be fixed including a small pinhole GN2 leak(s) from one or more of the shrouds. Therefore, a concerted effort to find and fix these small leaks was started in 12/95. Also, blankets of multi-layered insulation (MLI) were hung in the chamber between the chamber walls and the wall shrouds. However, no blankets were installed on the chamber bottom endbell. Three leaks around 2-in Al/SS bimetal joints and one leak at an 8-in feed line Al/SS bimetal joint were discovered. These faulty bi-metal joints were replaced. Three subsequent vacuum test trials were required before all welds were finally leak-free. Finally, the 25-ft SS was ready for its chamber cleanliness baseline bakeout.

The bakeout was conducted on 3/7-8/96. The chamber shrouds were heated to a temperature of 80°C for a period of 16.5 hours. Two temperature-controlled quartz crystal microbalances (TQCM) were mounted inside the chamber to measure outgassing rates, one facing horizontally downward and one facing vertically towards the shroud wall. A first TQCM measurement was made with the crystal at 40°C to ensure the outgassing rate wasn't excessive before lowering the TQCM temperature. Five subsequent TQCM readings were done at three hour intervals with the crystal at 0°C. The latter three of these readings showed that the outgassing rate had stabilized at about 675 Hz/hr, indicating that no further baking was needed. A final TQCM measurement was made with the crystal at -20°C yielding 30 Hz/hr for the horizontal TQCM and 70 Hz/hr for the vertical TQCM. At the end of the bakeout, the chamber pressure was 4.5 x 10^{-6} torr. The chamber was returned to atmospheric conditions and deemed clean and ready for MPF-STV testing.

FABRICATION AND BAKEOUT OF A SUN SHADE FOR THE MPF-STV-1 TEST IN THE 25-FT SS (9)

The MPF spacecraft will be spinning on its centerline axis as it travels to Mars to normalize the temperatures on the backshell and the radiators, thus distributing evenly the thermal effects of the solar radiation on these surfaces. In 10/95, discussions began regarding how to provide a constant solar flux to the backshell and HRS-radiators both of which would be shaded from solar beam by the MPF solar panel. After reviewing several alternate ideas, a decision was made to design and build a fixture consisting of several arrays of IR lamps to provide the needed solar flux simulation. This fixture is described below in the MPF-STV-1 discussion.

Once the fixture had been designed and was being fabricated, another problem needed to be solved. Using the existing installed optics in the 25-ft SS, the solar beam has a diameter of about 19.5-ft. By changing the integrated lens unit, a smaller beam diameter of 15-ft could be achieved. However, the spacecraft required a beam diameter of about 12-ft because a wider beam diameter would partially shine upon the fixture, heating the fixture and possibly skewing the uniformity of the simulated solar beam. To solve this problem, a sun shade with a 12-ft diameter aperture was fabricated and mounted above both the fixture and the spacecraft.

The sun shade consisted of an aluminum beam substructure with a fluoroglass material covering. However, since the fluoroglass covering would be directly impacted by the 25-ft SS solar beam during the MPF-STV-1 test, for contamination control reasons it needed to be baked to a temperature above that which it would potentially reach during MPF-STV-1.

The sun shade bakeout was conducted in JPL's 10-ft SS on 3/18-21/96. The larger fluoroglass pieces were draped in sections over two aluminum tubes (supported by cables) and the smaller pieces were laid directly on the floor shrouds. The wall and floor shrouds were heated to a temperature of 140-145°C to drive the material pieces to a temperature of 140°C. The material was baked at 140°C for 42 hours until the pressure and the water vapor content in the chamber stabilized at about 12% (determined by RGA readings) at a chamber pressure of 2 x 10^{-6} torr. After the bakeout, the fluoroglas was installed on the sun shade aluminum substructure in the 25-ft SS.

PROOF-OF-CONCEPT OF THE MPF-STV-2 TEST CONDITIONS IN THE 25-FT SS (10)

In January, 1996, planning for the cruise phase (MPF-STV-1) and the lander phase (MPF-STV-2) solar thermal vacuum testing of the MPF spacecraft was well underway when I was admonished by a long-time veteran of the 25-ft SS operations to study carefully the effects of creating a Mars environment in the 25-ft SS. There were a number of concerns voiced, most notably, that the chamber stainless steel shell possibly may overcool during the -135°C, 8 torr test condition causing ice to form on the chamber external surface. This ice formation, it was feared, may consequently cause overcooling of the carbon steel welds that connect the structural stiffener rings to the chamber shell and possibly cause the welds to crack and fail. If such cracks in the welds did occur, a risk of a catastrophic failure caused by collapse of the chamber wall could be the result. There were additional concerns about overcooling other primary chamber components including the door and door seals, the fused quartz solar window, electrical and instrumentation feedthrough connections, and others. To allay these concerns, a proof-of-concept test was devised to demonstrate that the chamber could safely provide the required Martian surface environmental test conditions for MPF-STV-2 without damaging any facility hardware.

The proof-of-concept test was conducted on 4/1-3/95. The test plan called for adjusting the chamber pressure to 8 torr with back-filled GN2 after roughing, then cooling the shrouds in two steps to the coldest temperature expected for the MPF-STV-2 test (first to -85°C then to -135°C). At each step, the temperature of the chamber

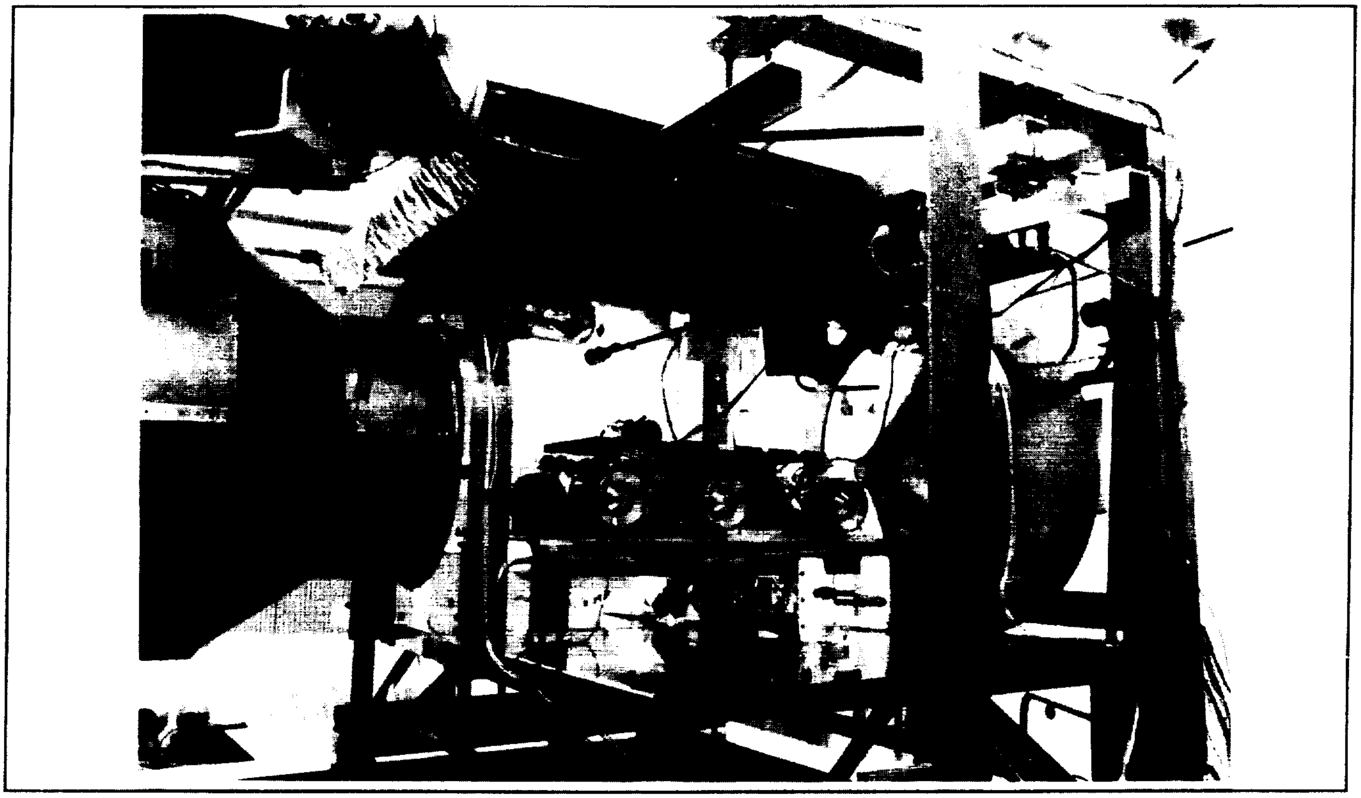


Figure 15. Photograph of the Mars Rover Engineering Model SIM QUAL Test Set-up

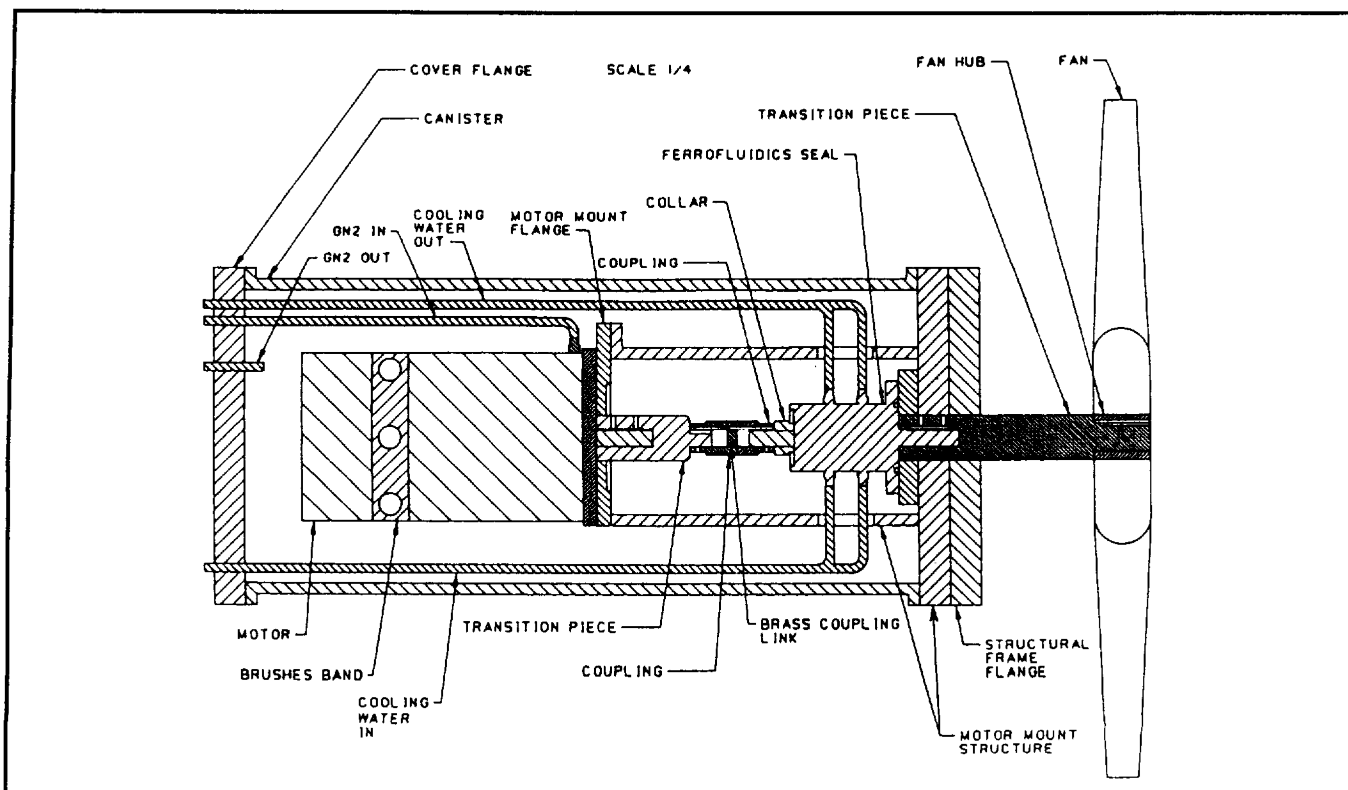


Figure 16. Wind Machine Drive Linkage Detail

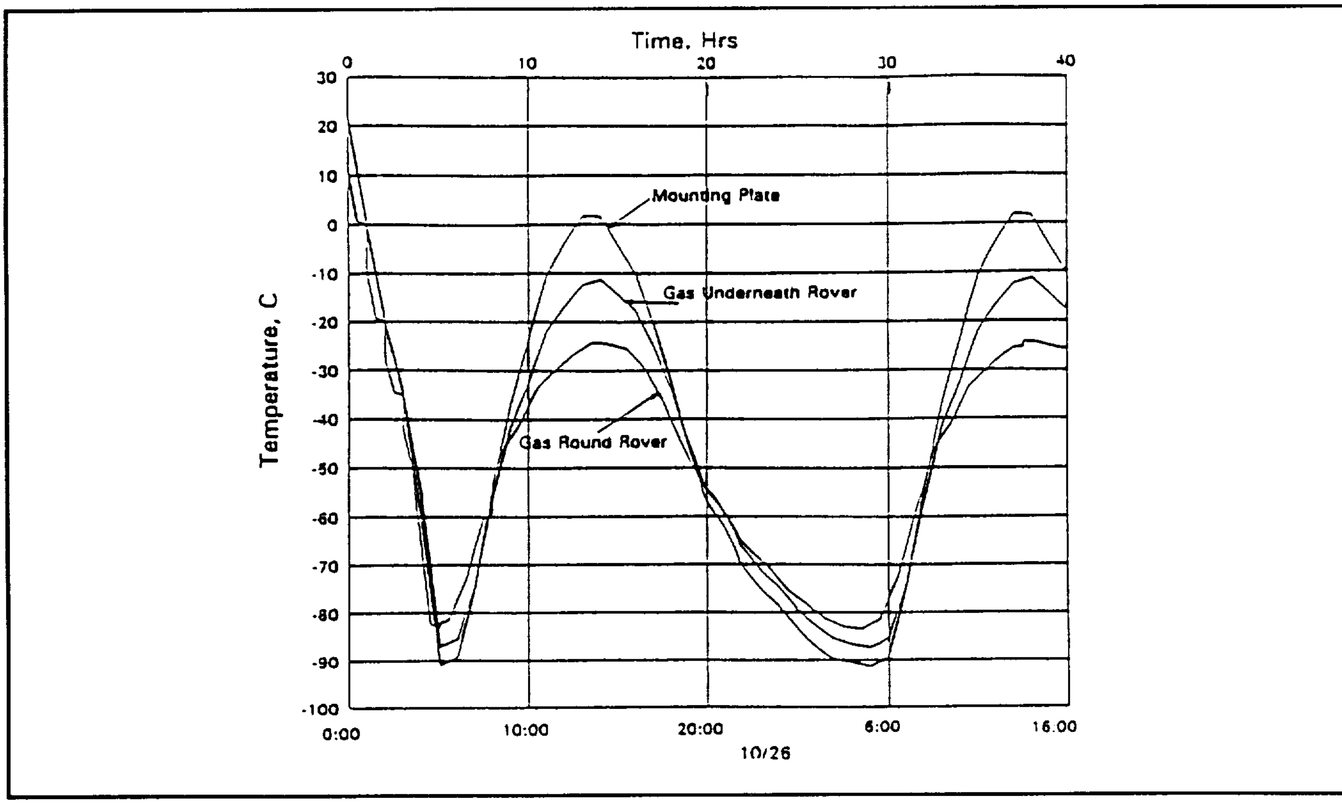


Figure 17a. Prescribed Mars Environmental Temperature Profiles for SIM-Q2a

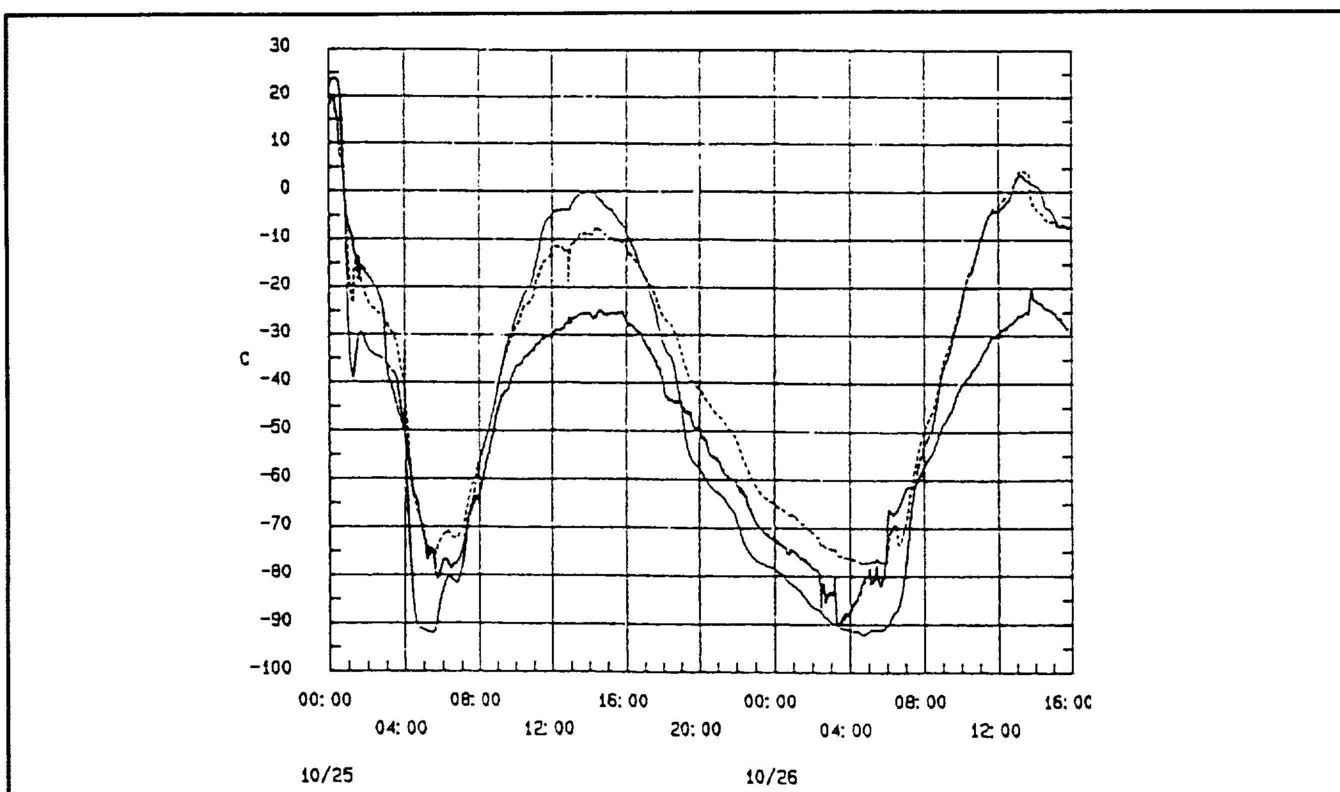


Figure 17b. Measured Mars Environmental Temperature Profiles for SIN-Q2a

shell and the carbon steel welds were carefully monitored at several locations to study the rate of cooling on the chamber external surface and to determine where frost or ice would first appear.

Results of this test indicated that no external chamber surface ever reached a temperature lower than 3°C. This lowpoint temperature was measured on the bottom endbell near a chamber feedthrough where cold gas was entering the chamber to cool the shrouds. Considerable condensation on the chamber bottom endbell was observed (since this endbell internal surface was not MLI-blanketed) but no frost or ice formed anywhere except on shroud feed lines (where it normally and typically has been observed to form). The temperature of the door and the fused quartz window frame remained well within acceptably safe limits throughout the test. Therefore, this proof-of-concept test showed that the MPF-STV-2 test conditions could be generated safely.

MPF-STV-1, THE MPF FULL ASSEMBLY CRUISE PHASE THERMAL RESPONSE TEST (11)

The MPF-STV-1 test planning began in 10/95 and by 4/15/96 all fixturing and instrumentation was ready for the test to begin. The thermal plan for this test test was prepared by J. Lyra. This test was conducted in JPL's 25-ft SS in two parts, the first part from 4/15 to 4/23/96 and the second part from 4/29 to 5/5/96. The objectives of this test were: 1) to demonstrate that the MPF spacecraft thermal design satisfies the various MPF component safe minimum/maximum temperature specifications when subjected to the most extreme environments expected over the life of the mission; 2) to obtain thermal test data to be used to correlate the analytical thermal models, to characterize the thermal behavior of various spacecraft equipment, and to determine design changes to correct any found thermal design deficiencies; 3) to verify that the spacecraft operates within the specified performance requirements and within flight allowable limits in simulated near Earth and near Mars space environments; and, 4) to verify that flight temperature sensor readings agree with comparable thermocouple readings.

Figure 18 is a photograph of the test set-up, including the sun shade, which was taken just prior to the start of MPF-STV-1. The solar fixture was made in five modular structural sections that were attached to a pentagon hub at the base. This fixture consisted of four distinct IR lamp arrays. Two of the arrays, the backshell lamp array and the HRS-radiator lamp array, were used to simulate the solar illumination on the sides of the spacecraft, since the spacecraft in flight will not always be situated such that the solar panels are directly normal to the sun (i.e., the spacecraft sides will not always be shaded by the solar panel). The backshell lamp array consisted of forty 14-in lamps. The HRS-radiator lamp array consisted of thirty 14-in lamps. In addition to these two arrays, two other safety lamp arrays were installed. The purpose of these safety lamps was: 1) to provide a way to warm the solar panel in case of a failure in either the solar simulation system or the facility power system, and 2) to provide a way to warm the heatshield in case of a facility power failure or any other unexpected overcooled condition on the heatshield. The safety lamp arrays were wired to be operated on emergency generator power. A special floor for the chamber was fabricated and installed to provide structural support for the backshell solar fixture. Both the fixture and floor were made of aluminum and were steam cleaned to remove hydrocarbon contaminants prior to being installed in the chamber. The sun shade can be seen located above the backshell solar fixture. The spacecraft was suspended about four feet above the chamber floor, hung by three cables attached to hard points on the chamber wall.

An infrared radiometer (IR) camera was mounted on the pan-tilt platform of the Satellite Test Assistant Robot (STAR, ref. 10) to provide thermal imaging of the solar panel throughout the MPF-STV-1 test.

The MPF-STV-1 test plan called for four test phases. Phase 1, the Mars Cruise-Fault Condition (1.55 AU, 0° Off-Sun orientation), a test which represented the worst case cold condition for the backshell, the lander and the cruise stage equipment, consisted of four test cases: 1-1) an accelerated cooldown of the test hardware after one pumpdown, GN2 backfill, and re-pumpdown (the accelerated cooldown for this test was done with the chamber at 8 torr GN2. No direct LN2 discharge into the chamber was used to accelerate local cooling); 1-2) a cold margin test to demonstrate the functionality of the cruise stage and lander stage electronics in the mission extreme cold environment (worst case cold condition for the backshell, the lander and the cruise stage equip-

Figure 18. Photograph of the Test Set-up for the MPF-STV-1 (Cruise Phase) Test in JPL's 25-ft Space Simulator

ment); 1-3) a thermal balance period to achieve steady-state conditions and to verify thermal designs in this orientation; and 1-4) a test to verify the functionality of the thermostatically-controlled back-up heaters.

Phase 2, the Mars Cruise-Nominal Cold phase (1.55 AU, 41° Off-Sun orientation), a test which represented the worst case cold condition for the solar array, consisted of six test cases: 2-1) a thermal balance period to achieve steady state and to verify thermal designs in this orientation; 2-2) a thermal simulation of a trajectory correction maneuver (TCM) for the propulsion hardware under cold conditions to measure the valve temperatures at the end of the maneuver; 2-3) a test to demonstrate that the basepetal airbag heater is sized properly to maintain the airbag at acceptable flight temperature limits; 2-4) a simulation of the entry, decent and landing (EDL) sequence beginning 95 minutes prior to landing for the purpose of characterizing the warm-up of the ISA, specifically the solid-state power amplifier, after the HRS pump is off, and to verify the EDL heater sizes; 2-5) a test to characterize the thermal response of the ISA equipment, the rover, and the cruise shunt limiter (SLC) in case of an HRS failure and to develop a strategy for thermal recovery of this equipment after such a failure occurs; and 2-6) a hot margin test of the ISA electronics to demonstrate the functionality of these electronics in the mission extreme hot environment.

Phase 3, the Earth Cruise-Nominal Solar Array Hot phase (0.99 AU, 0°C Off-Sun orientation), a test which represented the worst case hot condition for the solar array, the shunt radiator and the deep space station heads, consisted of one test case: 3-1) a thermal balance period to achieve steady-state thermal conditions to verify that the solar panel and other cruise stage hardware stays within acceptable flight temperature limits.

Phase 4, the Earth Cruise-Nominal 60° Hot phase (0.99 AU, 60° Off-Sun orientation), a test which represented the nominal hot condition to verify flight acceptable temperature limits. consisted of five test cases: 4-1) a test to verify the proper functionality of the two HRS pumps under hot conditions; 4-2) a test to verify the performance of the battery and its charging system at design temperature; 4-3) a thermal balance period to achieve steady-state thermal conditions to verify flight acceptable temperature limits; 4-4) a test to simulate a trajectory correction maneuver for the propulsion hardware under cold conditions; and 4-5) a hot margin test to demonstrate the functionality of the cruise stage electronics in mission extreme hot conditions.

Results of the MPF-STV-1 test were still being analyzed at the time of this writing and a final test report on the thermal response results is not yet available . However, all MPF-STV-1 test objectives were met.

MPF-STV-2, THE MPF FULL ASSEMBLY LANDER PHASE THERMAL RESPONSE TEST (12)

The final test in the MPF series, MPF-STV-2, was conducted to study the thermal response and performance of the lander equipment and systems, and to test the performance of the rover hardware mechanisms and command software in a simulated Mars surface environement. The thermal plan for this test was prepared by H. Awaya.

Figure 19 is a photograph of the MPF-STV-2 test set-up. A structurally supported perforated aluminum floor was steam-cleaned then installed in the chamber above the floor shrouds to provide structural support for the lander and the rover "doghouse". The lander was configured in a fully deployed position and the basepetal was supported on three 8-in high thermal isolative standoffs to ensure that all lander components would not come in direct contact with the floor of the chamber. The three sidepetals were supported on retracted airbags, in a simulated normal landed configuration. Because of biocontamination concerns, the lander solar panels were kept covered during the test.

The rover was mounted on one of the sidepetals and the rover ramp was deployed to allow the rover to drive off the petal during the test. A special semi-circular rover floor was fabricated to provide a surface on which the rover could transverse during the rover maneuverability tests. This floor was made of fluoroglass and was painted to provide a surface with medium absorptivity and emissivity similar to the optical properties of the surface of Mars. A white tape grid was laid down on the rover floor to provide a visual reference of the rover's position during maneuvers. An obstacle was placed on the floor in the path that the rover was expected to

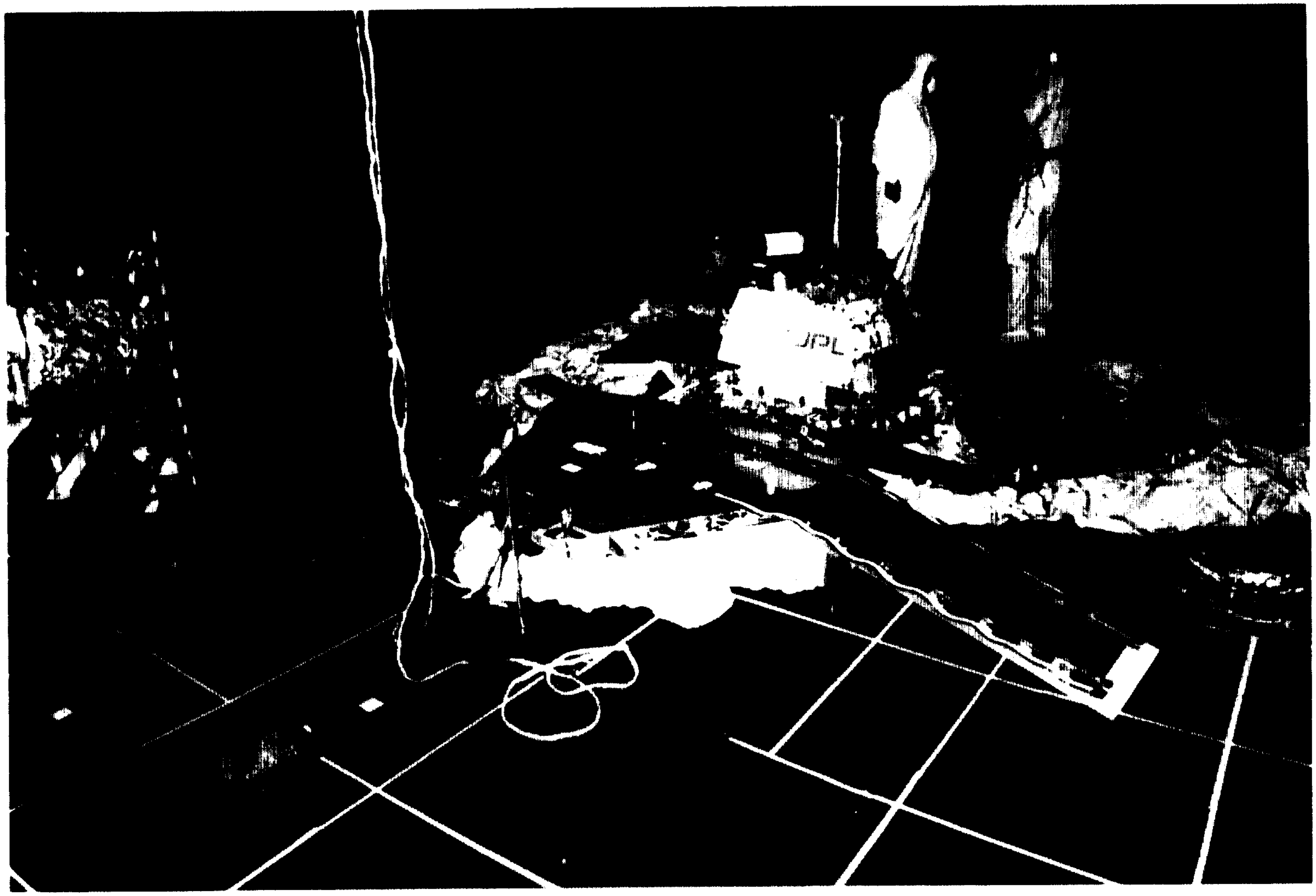


Figure 19. Photograph of the Test Set-up for the MPF-STV-2 (Lander Phase) Test in JPL's 25-ft Space Simulator

travel during the maneuverability tests. Cabling to provide communications and power to the rover was blanketed for thermal insulation and supported by a special skyhook arrangement. A rover "doghouse" was constructed with an aluminum frame, walls of reflective mylar and an infrared lamp assembly to keep the rover warm during the worst case cold test.

The test plan called for three test phases. Phase 1, the Mars Landed Diurnal Simulation phase, was a test to simulate the Mars landed environment at an atmospheric pressure of 7 torr GN2, to provide a 22 hour simulation of the diurnal solar and thermal surface conditions, and to maneuver the rover to test communication, imaging, roll-off, dead reckoning and a host of other important functional operations. Also during Phase 1, the Atmospheric Structure Instrument/Metrology (ASI/MET) Tavis pressure sensor was to be calibrated in the 1 to 9 torr range against a pre-calibrated Baritron pressure gauge attached to the chamber. Phase 2, the Mars Cold Steady State and Margin Test phase, was a test to obtain thermal characterization data for the lander in the cold case (nominally -85°C). Since the lander never obtains steady state operations during landed operations because of diurnal temperature cycling and internal power dissipation, the Phase 2 testing was done to determine the values of the thermal radiation, convection, and conduction components in a stabilized condition in order to properly characterize the thermal response of the electronics and other hardware and to verify that the response is within acceptable flight temperature conditions. Phase 3, the Mars Hot Steady State and Hot Margin Test, was performed for reasons similar to those given for Phase 2, except the test was conducted at the hot stabilized conditions (nominally -40°C).

The thermal results of the MPF-STV-2 test were still being analyzed at the time of this writing and a final test report on the thermal response results is not yet available. However, all MPF-STV-2 thermal test objectives were met. The rover maneuverability test was conducted by manually commanding the rover to travel from its mount on the petal, down the ramp, past the obstacle, and into the doghouse. The STAR system was used to provide visual feedback to the rover engineers of the rover's position during maneuvers. Further details of the rover maneuverability test will be described in a separate report. Much useful information was obtained during this test which helped both the MPF lander thermal engineers and the rover design team to improve and fine tune the various functions of the MPF lander thermal system and the rover hardware and software.

CONCLUSIONS

The MPF test program was an important part of the verification of the designed functional performance of the MPF systems during both the cruise and landed mission phases. The test program was very challenging to test designers and required the development of many new test methods and fixtures. The program proved to be very valuable in assisting the MPF thermal engineers and the rover design team to discover some design anomalies in a way which provided enough time to make any necessary design changes prior to launch. As such, the test program was very effective in helping the MPF design team to ensure the success of the overall MPF mission.

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