# Mars Microprobe Project Instrumentation Package

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## ABSTRACT

The Mars Microprobe Project is a technology validation mission in NASA's New Millennium Program. The project is developing a pair of small, two-piece probes for delivery to the surface of Mars in December of 1999. Descent from orbit to the surface is accomplished with a passive single-stage non-erosive aeroshell designed specifically for this mission. Upon impact each probe separates into a section that penetrates into the Martian regolith and a section that remains on the surface. This design provides an opportunity to collect scientific data both on and up to two meters beneath the surface. The instrumentation package of the Mars Microprobe includes a meteorological instrument for measuring atmospheric pressure and temperature, accelerometers to measure the atmospheric drag on the probe aeroshell during descent, accelerometers for measuring the forces on the probe at impact, temperature sensors in the penetrator to measure the soil thermal conductivity at depth, and an experiment to collect a small sample of the Martian regolith and determine if water is present in the sample. An overview of the instrument design and implementation is reported along with the results of the environmental tests and instrument calibration.

## 1. Introduction

The Mars Microprobe Mission is the second spacecraft developed as part of the New Millennium Program deep space missions. The objective of the Microprobe Project is to demonstrate the applicability of key technologies for future planetary missions by developing two probes for deployment on Mars. The probes are designed with a single stage entry, descent, and landing system and impact the Martian surface at speeds of approximately 200 meters per second. The microprobes are composed of two main sections, a forebody section that penetrates to a depth below the Martian surface of 0.5 to 2 meters, and an aftbody section that remains on the surface. Each probe system consists of a number of advanced technology components developed specifically for this mission. These include a non-erosive aeroshell for entry into the atmosphere, a set of low temperature batteries to supply probe power, an advanced microcontroller to execute the mission sequence, collect the science data, and react to possible system fault conditions, a telecommunications subsystem implemented on a set of custom integrated circuits, and instruments designed to provide science measurements from above and below the Martian surface. All of the electronic components have been designed and fabricated to withstand the severe impact shock environment and to operate correctly at predicted temperatures below -100° C.

## 2. Mission Overview

The Mars microprobes are launched as a technology payload on the 1998 Mars Surveyor Lander mission in January of 1999. The mission trajectory places the Mars Surveyor Lander and the microprobes at about 71° south latitude on Mars in December of 1999. During the 11 month cruise period from Earth to Mars, the microprobes are unpowered and no communication is possible with ground controllers or the Mars 98 spacecraft until the first telecommunication opportunity after impact. When the 1998 Mars Lander separates from the spacecraft cruise stage, a mechanical pyrotechnic device is fired which releases the two microprobe flight systems and applies the system power to the microprobe electronics. The atmospheric aeroshell entry system passively orients the microprobes for descent to the surface and impact without the need for propulsion, attitude knowledge, or parachutes. Upon reaching the surface, approximately six minutes after release, the aeroshell shatters and the microprobe penetraters are deployed. The expected peak deceleration force on the forebody, which penetrates up to a depth of 2 meters, is 30,000 g's. The aftbody, which remains within 5 cm of the surface, must withstand a peak shock of 80,000 g's. The fore and aftbodies are connected by a flexible umbilical cable for power and data transmission between the two portions of the microprobe. Installed in the aftbody section of the microprobe are lithium thynol-chloride batteries that have been developed to survive the impact shock and provide power down to temperatures of -80° C. The microprobe, as deployed on Mars is shown in Fig 1.

## 3. Power Micro-Electronics Subsystem

All spacecraft are constrained by the electrical power available for operating the on-board avionics. This situation is particularly severe for the microprobe mission. The necessity to keep the mass of the batteries down, coupled with the low mission operating temperature requires an intelligent allocation and management of the power during the mission. To enable the efficient use of the power resources, a custom Power Micro-Electronics Subsystem (PMEU) has been developed to convert the battery supply voltage of 9 to 11 Volts to the 5 and 3.3 Volts needed by the spacecraft and to allow the flight software to connect and remove loads according to the mission sequence. The PMEU consists of two custom integrated circuits to implement both linear and switching regulation, to prevent over current conditions due to power faults, and to provide an interface for software to control the loads connected to spacecraft power. The PMEU was developed for the Microprobe project by Boeing Corporation's Space and Defense Group.

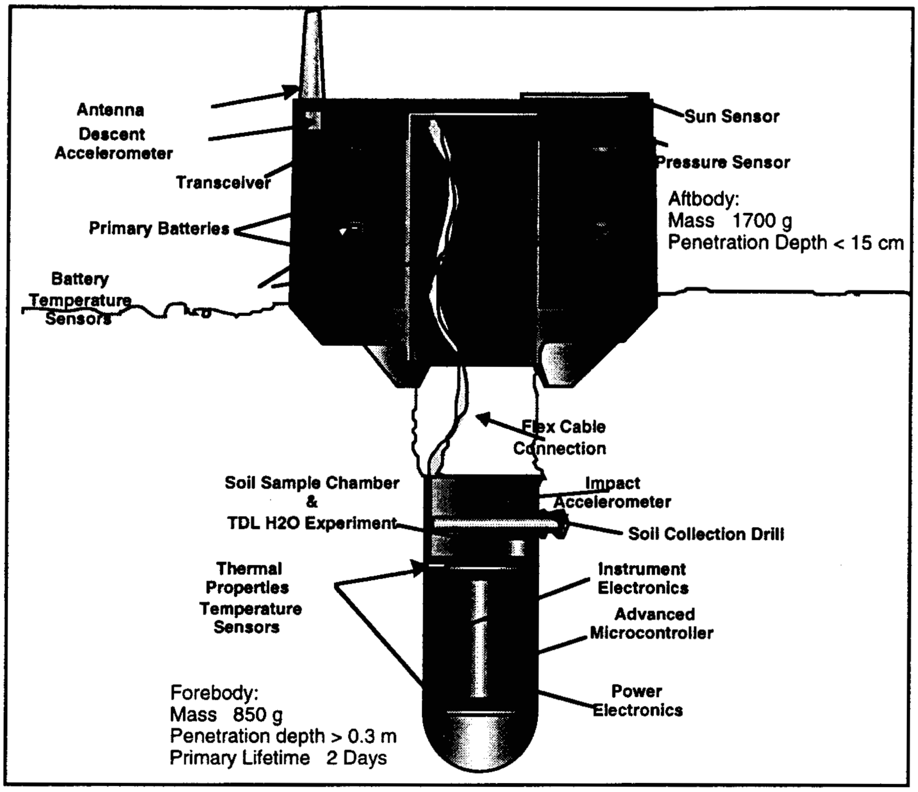


*Figure 1 Mars Microprobe After Landing*

## 4. Advanced Micro-Controller

Operation of the microprobes on the Martian surface is completely autonomous . The probes have no capability of receiving any modifications to the flight software that may result from analysis of data on the ground. The control of the probe instruments, collection of science data, execution of the mission sequence, and detection of and recovery from fault conditions is accomplished with a custom designed Advanced Micro-Controller (AMC) developed jointly by the Air Force Phillips Lab and Mission Research Corporation. The AMC consists of an 8051 type of microprocessor, an analog module with a 32 input A/D converter, an EEPROM for storing the mission software, and 128k bytes of SRAM. In order to conserve power, the AMC can be programmed to autonomously enter a low power sleep mode which only consumes 600 $\mu$Watts of power. At programmed intervals during the mission the AMC will return to the normal operational mode to acquire and store science measurements.

## 5. Mars Microprobe Instruments

The Mars Microprobe instruments have been selected to take advantage of the penetrator's unique capability to gather data both on the Martian surface and at depth. The instrument package includes a atmospheric descent accelerometer to measure the drag forces on the aeroshell during entry; a meteorological sensor to provide data on the atmospheric pressure and temperature; an impact accelerometer to measure the deceleration forces upon impact with the surface; a pair of precision temperature sensors to record the cooling rate of the forebody beneath the surface; and an experiment to collect a subsurface sample of Martian regolith and examine the sample for water content. Each of these instruments are described in detail in the following sections.

### 5.1 Atmospheric Descent Accelerometer

A unique, single stage, non-erosive aeroshell has been developed for the Mars Microprobe Mission. The aeroshell will enable the microprobes to be released at any orientation and spin rate from the cruise vehicle. Performance of the entry system during descent is measured by monitoring the atmospheric drag forces on the aeroshell with an accelerometer. A commercially available accelerometer, manufactured by Analog Devices, has been selected for this purpose. The internal sensor is a micromachined silicon beam that is displaced by acceleration forces along the device's sensitive axis. This displacement is sensed by measuring variations in capacitance between plates mounted on the silicon beam. Integrated with the micromachined silicon sensor on a single monolithic substrate are the signal conditioning electronics needed to interface the accelerometer to an analog to digital converter. The accelerometer has a measurement range of 0 to ±50g with an accuracy of 5 mg at a sample rate of 25 Hz. The drag forces information from the atmospheric accelerometer can be used to derive a density profile of the Martian atmosphere. Since the entry system relies solely on atmospheric drag on the aeroshell for deceleration, the Mars Microprobe Mission is the first opportunity to make atmospheric density measurements from orbit to the surface.

### 5.2 Impact Accelerometer

Deceleration during impact can produces forces as high as 30,000 g on the forebody section of the microprobe. A measurement of the impact force profile is made with a piezo-resitive bridge accelerometer that has a full scale measurement range of ± 60,000 g and a resolution of 10g. The microcontroller samples the accelerometer at a rate of 25 kHz during the latter portion of the atmospheric descent sequence of the mission and stores the 30 milli-seconds of data containing the impact event. After the data has been received on Earth, a double integration on the deceleration force profile is performed. This provides an estimate of the depth that the forebody penetrated into the Martian surface. In addition, if the microprobe forebody encounters soil layers of different densities during impact, the resulting change in deceleration will be evident from the accelerometer data.

### 5.3 Soil Thermal Conductivity Temperature Sensor

The microprobe will rapidly cool down to the ambient temperature of the soil after landing. Current predictions place the ambient temperature below the surface at -120° C. The rate of cooling is dependent on the thermal conductivity of the soil. Two platinum resistor temperature sensors, one near the nose of the forebody and another near the tail, measure the temperature of the forebody during the cooling to a precision of 0.01° C over the expected range of 5 to -100° C. The sensors are sampled once every 30 seconds for the first five minutes of the landed mission with the measurement sample rate decreasing to once every hour after the probe reaches thermal steady-state. Two sensors are used for this measurement to determine if the shape of the forebody influences the cooling rate.

### 5.4 Atmospheric Pressure Sensor

The aftbody section of the microprobe is designed to remain on the surface of Mars to enable communications between the microprobe and the Mars Global Surveyor spacecraft that serves as the relay link back to Earth. Installed on the aftbody is an atmospheric pressure and temperature sensor that is being developed from a commercially available sensor used in automotive and medical applications. The pressure sensor is designed around a micromachined, 1 mm diameter silicon membrane that has four strain sensitive resistors implanted in a bridge configuration. Changes in atmospheric pressure causes the flexible silicon membrane to deflect. This deflection is sensed by measuring changes in the piezo-resistors in the bridge circuit. Adjacent to the bridge resistors on the silicon membrane is additional single resistor that is used to measure the temperature of the sensor. Both the atmospheric pressure and temperature are sampled and recorded by the telecommunications subsystem. The telecommunications system can operate autonomously which enables acquisition of meteorological data in the event that the microcontroller failed during the impact.

### 5.6 Evolved Water Experiment

The primary instrument on the Mars Microprobe is the Evolved Water Experiment. The experimental priorities are to: collect and isolate a subsurface sample of the Mars soil; to detect the presence of water ice as a constituent of the sample; and to determine if the sample contains bound water in hydrated mineral states.

Collection of the sample is accomplished by a small, ruggedized electric motor and drill mechanism. When power is applied to the motor, the drill retention latch is released and the drill shaft begins to extend horizontally from the side of the forebody into the surrounding soil. The drill operates at 10 rpm for approximately 6 minutes and transports about 100 mg of soil material down the flutes of the drill into a small, 6 mm diameter, heater chamber. During the drilling operation, the motor current is monitored by software in the microcontroller to detect if a stall condition occurs. If a stall is detected the microcontroller will pulse the power to the motor to attempt to free the motor and continue the experiment. Upon completion of the drilling operation, a small pyrotechnic device is ignited that will cause a cover to seal the top of the heater chamber and isolate the sample from the environment.

The heater chamber that contains the sample is constructed of a ceramic material that has a nichrome heater element embedded in the wall. Installed in the chamber are two thermistor type temperature sensors, one on the inner wall and another on a small post located in the center of the chamber. Since the thermal inertia of the chamber will be altered by the presence of a sample, the pair of temperature sensors are used to verify that a sample has been collected. As the sample is heated, vapor that evolves from the sample flows through a small orifice in the bottom of the chamber into an adjacent analysis chamber where the spectroscopy measurements are made.

The evolved vapors from the sample are illuminated by light from a tunable diode laser (TDL) whose nominal operating wavelength can be tuned by varying both the laser temperature and input current. The output signal from the TDL is collected onto and measured with a InGaAs photo detector. The TDLs used for the Mars Microprobe have been selected to have a nominal optical wavelength of 1.37 μm where a strong absorption line of water vapor is located. In operation, the temperature of the TDL is regulated by a closed loop proportional controller. The temperature controller must be capable of maintaining the TDL temperature within 0.2° C of the nominal 20° C operating point to ensure that the water absorption line is observed if water vapor is present in the analysis chamber. The TDL optical wavelength is scanned by applying a 1 Hz ramp to the input current. This current ramp, effectively scans the optical wavelength by 5-8 Å around the

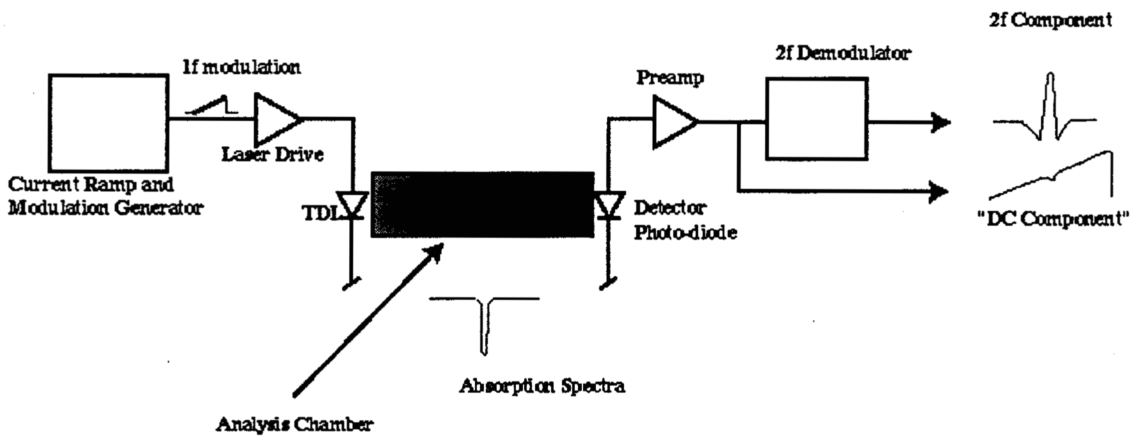


***Figure 2***
***Water Experiment Demodulation Technique***

nominal 1.37 μm operating wavelength. Superimposed on the current ramp is a 5 kHz quasi-sinusoidal modulation whose amplitude is approximately 10% of the amplitude of the ramp signal. After the signal that has been transmitted through the analysis chamber is collected on the photodetector, the resulting electrical signal is demodulated at a frequency of 10 kHz, or twice that of the original modulation frequency. The 2f demodulation technique, which is shown schematically in Fig 1, produces a signal that is proportional to the second derivative of the slowly varying unprocessed signal. The 2f demodulation technique produces an absorption signal with a greatly improved signal to noise ratio over the unprocessed signal directly from the photodetector. The greatly enhanced sensitivity from this measurement technique allows the evolved water experiment detect vapor that evolves from samples that contain as little as 0.1% water.

## 6. Mission Operational Sequence

Since the Mars Microprobes can not be commanded after launch, all mission operation and sequencing is performed autonomously by the on-board microcontroller. The mission sequence as executed by the microcontroller is shown in Fig. 3 and is described in detail in the text.

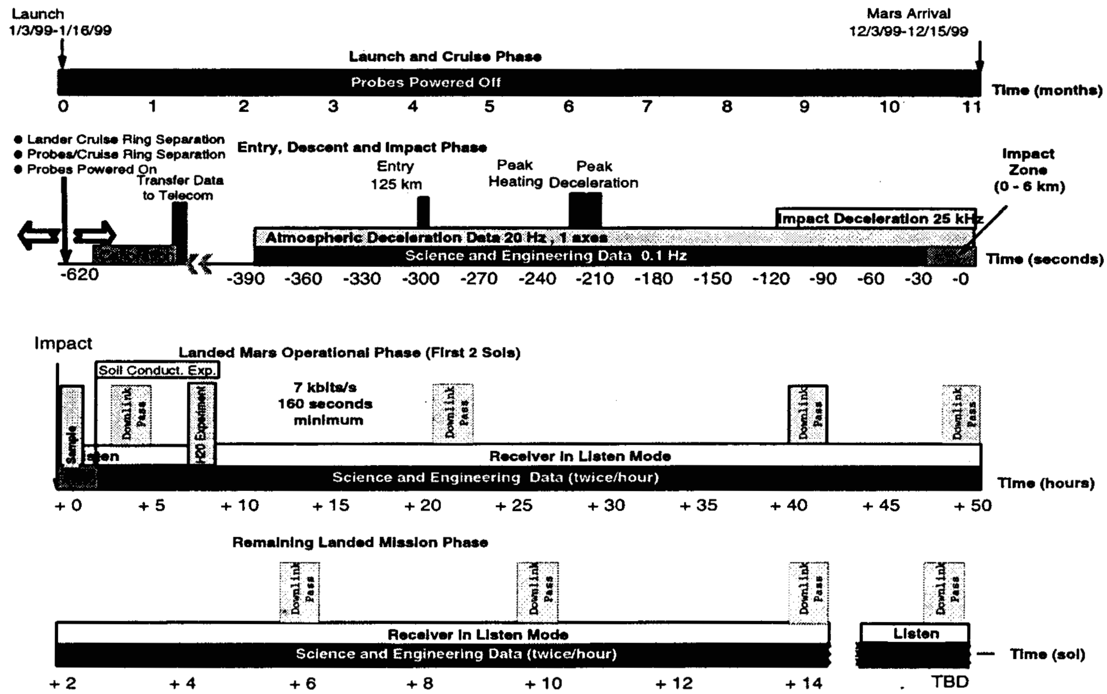


*Fig 3. Mars Microprobe Mission Sequence*

### 6.1 Entry, Descent, and Landing

Upon release from the cruise stage of the Mars Surveyor spacecraft, power from the microprobes primary lithium batteries is connected to the main power bus. In the forebody of the penetrator the microcontroller, which controls the mission sequencing and collects data from the instrument package, becomes active. When power is initially applied to the microcontroller at the start of the mission, it performs a series of measurements of the on-board subsystems to verify their health after the cruise to Mars and to establish a pre-impact operating point for the instruments. Prior to atmospheric entry, the pressure sensor is examined to establish if the zero pressure baseline has shifted since the instrument was calibrated. Readings from temperature sensors located at various positions on the microprobe are recorded. The evolved water experiment is powered, and the output power of the tunable diode laser is measured to verify its health prior to impact.

About 250 seconds after power initialization, the atmospheric entry portion of the microprobe mission sequence begins. The descent accelerometer is powered on and the deceleration forces due to atmospheric drag are sampled at a constant rate of 20 Hz until impact. After an additional 260 seconds, the microcontroller initiates the impact detection sequence and begins sampling the impact accelerometer at a rate of 25 kHz. The data from the impact accelerometer is stored by flight software in a circular memory buffer. Upon detection of the impact, the impact event data is stored, and the impact accelerometer is turned off.

The landed phase of the Mars Microprobe mission begins immediately after impact. The microprobe collects voltage and temperature telemetry from the batteries to determine if all battery cells have survived the impact deceleration forces. Based on the state of the batteries, the microcontroller determines if sufficient battery power is available to enable the evolved water experiment sequence.

**6.2 Evolved Water Experiment Sequence**

The evolved water experiment sequence is designed to verify that the three priorities of sample collection, ice detection, and hydrated mineral detection have been accomplished. Prior to sample collection, the empty sample chamber heater is powered on and the temperature is increased until it is about 40° C above the chamber's starting temperature. The heater power is then removed, the chamber cools to it's original temperature and the heating and cooling profiles are recorded. The empty sample chamber temperature profile provides reference data that will be used for comparison with the thermal characteristics of the chamber after the sample has been collected. After the chamber has cooled, the drill motor is powered on for a period of six minutes. The drill mechanism extends out of the side of the microprobe forebody and collects a sample of sub-surface regolith. When the drilling is complete and the sample is in the heater chamber, a small pyro device is fired to actuate a cover to seal the chamber and isolate the sample.

Once the sample has been isolated from the environment, power is again applied to the sample heater. The temperature of the sample in the chamber is increased by about 40° C above its initial temperature but no more than -20° C to ensure that ice that may be in the sample is not sublimated, and the heating profile is recorded. At -20° C heater power is removed, and the sample is allowed to cool back to the starting temperature. The thermal characteristics of the full sample chamber will be compared to those previously recorded for the empty chamber to verify that sample collection was successful.

The preceding sample verification portion of the water experiment is based solely on the thermal characteristics of the sample chamber before and after the sample is collected. In order to determine if water ice is a constituent of the sample, the tunable diode laser spectrometer is needed. The sample heater is powered and the temperature of the sample is increased to 0° C. The power of the optical signal transmitted through the vapor that evolves from the sample is measured using the 2f demodulation technique described previously. If water vapor is detected, 32 samples along the wavelength scan around the water absorption peak are recorded. Assuming that the ice is homogeneously distributed in the sample, the temperature measurements of the sample will remain at 0° until all the ice in the sample has sublimated. The sample temperature is then increased to 10° C and held there for five minutes to ensure that the sample is cleared of water ice to prepare for the hydrated mineral detection portion of the experiment. The power to the heater is removed and the experiment is allowed to cool to the ambient temperature of the surrounding environment.

The amount of water vapor that is likely to be released during the preceding ice detection sequence experiment is significantly greater than any amount that could evolve from the presence of hydrated minerals. Therefore, in order to discriminate between the two potential sources of water, it is important that any residual vapor that may have evolved from the sample during the ice detection sequence be removed from the optical path of the TDL spectrometer. The analysis chamber that contains the laser and detector has a small vent to allow the vapor to diffuse out of the spectrometer's optical path onto the inner surface of an external wall of the penetrator. The surface of the wall, that is at the surrounding temperature of -100° C, will act as a cold trap and collect the vapor. By allowing the experiment to cool for a few hours, all of the water vapor can be condensed out of the system in preparation for the high temperature, hydrated mineral detection portion of the water experiment sequence.

Detection of hydrated minerals requires that the sample be heated to temperatures between 100° to 500° C. This portion of the water experiment consumes a significant amount of the total battery energy available for this mission. Therefore, prior to starting this sequence, the microcontroller determines the state of the batteries by measuring the battery temperature and voltages. If the batteries appear to be in a nominal condition, the microcontroller will wait until one telecom transmission event has been completed before running the final segment of the water experiment. The wait could be as long as several days without affecting the results of the hydrated mineral experiment. If a determination to run the experiment is made the sample will be heated at a controlled rate of 20° C per minute. The sample is heated until it is above 300° C or until the total energy allocation of 3000 Joules for the water experiment has been expended.

### 6.3 Meteorological Measurement and Secondary Mission Sequence

After the evolved water experiment has completed, the microcontroller prepares the data and sends it to the telecommunications unit for transmission to the relay link on the Mars Global Surveyor spacecraft. The microprobe telecommunication system transmits the data packets when it detects an identifying beacon signal from Mars Global Surveyor. Once each hour after the water experiment sequence has terminated, the meteorological sensor and the forebody temperature sensors are sampled and the data stored for transmission during the next telecommunication opportunity. The primary mission is scheduled to last about 50 hours, but since these meteorological measurements consume relatively small amounts of energy from the batteries, the microprobes could possibly survive, with best case environmental conditions, on the surface for up to 60 days.

## 7. Instrument Electronics Design and Environmental Test Results

Implementation of the instrument electronics for the Mars Microprobes is based on three critical factors.

First the small size of the microprobe severely restricts the area available for electronic components. The allocated substrate area for the water experiment electronics is 40 mm by 24 mm. This size limitation, along with the complexity of the circuitry needed to control the TDL, forces the electronics to either be realized in a custom mixed-signal ASIC or by directly attaching the integrated circuit die to a ceramic substrate. The budget and schedule for the microprobe instruments did not allow for the development of a custom ASIC. In addition, each TDL has individual characteristics that require that certain component values in the circuit be selected during test. The electronics have therefore been implemented by bonding die form active integrated circuits and chip passive components to a multi-layer ceramic circuit substrate.

The deceleration forces experienced by the microprobe presents a challenge to insure survivability of the instruments during the impact. Fortunately, the direct die attachment technique adopted for the electronics produces a strong, lightweight structure that is capable, with the addition of a thin conformal coating to protect the wire bonds, of withstanding the impact. However, other components in the instrument package require special mounting methods to provide some level of isolation from the impact forces. The TDL must be mounted in the water experiment analysis chamber with an elastameric compound to filter out the high level, high frequency components of the impact. Similarly, the atmospheric pressure sensor mounting uses a flexible adhesive to isolate the silicon membrane on the sensor and eliminate any mechanical strains which can not be distinguished from strains caused by changes in atmospheric pressure. Both the TDL and the pressure sensor, along with other critical components of the microprobe, have been extensively tested by firing prototype microprobes from an air gun operated by the Energetic Materials Research Test Center at New Mexico Institute of Mining and Technology. The microprobes are fired into prepared targets of soils of varying hardness at velocities equal to the predicted impact velocity on Mars. These tests have demonstrated, that by using that have been mounting methods developed for this mission, critical components used in the microprobe instruments will survive and function normally after landing on Mars.

The third critical factor that affects the design approach for the microprobe instruments is the harsh thermal conditions beneath the surface. While electronics and sensors on the aftbody will receive some solar heating, the forebody electronics will reach temperatures as low as -120° C. Proper operation of the instrument electronics at these temperatures requires that high precision components with very stable temperature performance be selected. Early in the design phase, several types of active components were screened to determine which devices would function with the least performance degradation. Thermal tests of a complete prototype of the experiment electronics have shown that the flight design will operate in specification down to -130° C.

## 8. Summary

The Mars Microprobe Mission provides a vehicle for deploying instruments on and below the surface of Mars. By selecting commercially available sensors and components when applicable and developing unique capability instruments when needed, the Mars Microprobe instruments will validate important technologies for future applications and provide a meaningful scientific return.

## 9. Acknowledgments

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