

THE MARS PENETRATOR TELEMETRY AND CONTROL SYSTEM

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Summary. A new method for exploring the planet Mars has been proposed* that will use ground-penetrating vehicles to carry scientific instruments below the Martian surface. The subsurface performance of various sequences of complicated experiments poses challenges in the design of the telemetry and control links. This article describes the overall mission, the penetrator, the constraints imposed by the mission and the penetrator, and a design for the telemetry/control system. This design uses a microprogrammed microprocessor; the sequences of commands are stored in a Read-Only-Memory (ROM), and a particular sequence is initiated by transmitting from the Earth the address in the ROM that contains the first of the commands for the specific sequence to be performed. Data from the experiments are stored in a memory for later transmission to an orbiter that serves as a relay station for the command and data links with Earth.

Introduction. The goal of landing scientific instruments on Mars can be achieved in at least three ways. First, it is possible to soft land an instrument package by using appropriate active techniques for a controlled descent; such a method has been chosen for the Viking Lander. The advantage of soft-landing is that instruments that are not shock-hardened can be used, but the corresponding disadvantage is that achieving such a soft landing is a difficult and costly task. A second method of surface deployment involves slowing the instrument package only through the use of passive devices, so that the instrument package experiences an abrupt deceleration at the surface. This is a technique that the Russians have used. The advantage of such a technique is that it is simple, whereas the disadvantage is that landing decelerations are on the order of 20,000 Earth g's, which requires extensive shock-hardening of the instruments. There is a third method, intermediate to the first two, that is the subject of this article. This third method involves using only passive devices to slow the instrument package, but differs from the hard lander in that it achieves shock mitigation by so shaping the instrument package into a long, sharp-pointed cylinder that the package penetrates the Martian surface for several meters. The ground penetration by these vehicles spreads the overall deceleration over both time and distance, thereby achieving a shock level that is an order of magnitude less than the

* Sandia Laboratories, "Mars Penetrator: Subsurface Science Mission," SAND-74-0130, August 1974, performed under NAS&/Ames Defense Purchase Requisition RA-88365-A. This work has been liberally quoted from in the present article.

shock for the hard lander. The advantages of such a scheme are that it is simpler and thus less expensive than a soft lander, and less shock-hardening of the instruments is required than for a hard lander. The disadvantages are that more Shock-hardening is required than for a soft lander, and the instruments must be so designed that they will fit into a long, slender cylinder. A fact that has both advantages and disadvantages is that the instruments are emplaced below the Martian surface.

A Mars penetrator mission has been proposed that will be complementary to the Viking Lander, and that will serve along with the Viking Lander to gather information that can be used for the planning of a sample return mission. The penetrator mission will involve the use of multiple penetrators that will be deployed from an orbiter. Each penetrator will be comprised of a forebody that will carry the scientific instruments below the Martian surface; an afterbody that stays at the surface and contains the high-shock-hardened transmitter, receiver, and antenna; and an umbilical between the two. After a penetrator comes to rest it will establish a communications link with the orbiting spacecraft for probe command and control purposes. A sequence of science experiments is then conducted either by command from the orbiter or under control of a preprogrammed sequence, and the data are stored in an onboard memory until they can be transmitted to the orbiter for relay to Earth.

Science. The use of the penetrator technique offers several unique features for science objectives:

- Multiple landing sites per orbiter
- Subsurface emplacement of science
- Capability of operating in polar regions
- Compatibility with a broad range of landing sites
- Tolerance of uncertainties about atmosphere, terrain, and terrain relief

Although many experiments are compatible with the penetrator concept, a science package incorporating experiments in vertical profile physical geology, geochemistry, and seismology has been selected to establish a baseline system design.

The penetrator will carry a high-frequency accelerometer the output of which will be double integrated to give the depth at which the forebody comes to rest. This deceleration record will provide a direct measurement of the penetrability and stratification of the Martian surface over the depth of the penetrator emplacement. These data, when compared

with similar data taken in analog Earth materials, will provide insight into the structure of the Martian subsurface.

Two remote chemical analysis techniques used on the moon are candidates for a penetrator mission; alpha-backscatter analysis and neutron activation analysis. There is little doubt the alpha-backscatter instrument can tolerate the penetration-induced environment; therefore, it is classified among the most compatible science instruments. The neutron activation instrument in its present form uses a thallium-loaded sodium iodide monocrystal in a scintillation detector in conjunction with a photo-multiplier. Both of these components are very susceptible to shock damage. For this reason the alpha-backscatter instrument was selected for the base line design. The alpha-backscatter technique involves illuminating a Martian soil sample with a source of alpha particles. The elements that are being illuminated can be detected by an analysis of the spectrum of the alpha particles and protons that are backscattered into the alpha and proton detectors that are part of the instrument. Thus by this technique certain of the elements of which Mars is composed can be determined, and subsurface measurement insures that the elements are from the undisturbed soil instead of from particles that may have been blown over the Martian surface or otherwise disturbed.

Passive seismological studies are eminently suited to the penetrator mission. The subsurface placement of the penetrator provides a superior coupling of seismic instruments to the surrounding soil. The penetrator can accommodate appropriate three-axis seismic instruments of two types: the Viking seismometer and the geophone. A typical mission will provide a minimum of four probes; thus deployment of the penetrators at different times as the orbit of the spacecraft precesses around the planet will automatically establish a dispersed seismic net.

Penetrator Delivery and Emplacement. Delivery and emplacement of the penetrators and their science payloads for subsurface exploration of Mars involves the combination of mechanical design, aerodynamics, and terradynamics. (Terradynamics is the branch of dynamics that deals with rapid penetration of earth materials.) This task is accomplished in three steps: (1) transport to a Martian orbit, (2) entry through the Martian atmosphere, and (3) emplacement into the Martian surface. Each part of the delivery sequence imposes demands, often competing, on the penetrator and entry system designs. For instance, compatibility with the spacecraft dictates a compact package, while atmospheric entry and deceleration require a large drag area. Also, successful penetration of a broad range of surface materials requires a slender, rather heavy vehicle, while launch vehicle and spacecraft capabilities dictate that the weight be kept as low as possible. Furthermore, accomplishment of scientific objectives requires subsurface emplacement of the payload, while communications of data to the orbiter requires that the antenna be at the surface.

A design concept, which accomplished the delivery of the penetrator to the surface and satisfies the competing demands of the spacecraft, atmospheric entry, and surface penetration, is illustrated in Figure 1. This concept is based on existing technology. The penetrator and its terminal deceleration system are packaged in a cylindrical canister which is in turn carried in the spacecraft launch tube. The canister provides a clean interface with the spacecraft launch tube and the deorbit rocket motor. In addition, the canister provides a biobarrier which minimizes the impact on the mission of a prelaunch failure of the primary biobarrier, the launch tube. Upon ejection from the launch tube, the canister is pneumatically extended to twice its original length to provide a high-drag first-stage decelerator and heatshield for atmospheric entry. At the appropriate time, the cylinder is removed, and a large parachute is deployed. This large parachute further decelerates the penetrator and orients it to near vertical. After the proper attitude has been achieved, the large parachute is released and a cluster of three small parachutes is deployed for terminal velocity control.

After the penetrator reaches the surface, it must be capable of emplacing the science experiments as deep as possible in the broadest range of materials without exceeding the deceleration limits of these experiments and support electronics. The penetrator must also maintain a communications link to transmit the data acquired from the subsurface probe. Figure 2 depicts how this is to be accomplished.

The Mars penetrator will be patterned after the over 10,000 seismic and acoustic sensor vehicles deployed in Southeast Asia on the McNamara line. In the Southeast Asia application the main body penetrated sufficiently deep to limit the deceleration to safe limits for the onboard sensors and electronics, and a detachable afterbody containing the antenna system was left on the surface. An umbilical cable was deployed as the forebody penetrated to provide the required link between the electronics and antenna system. In the proposed Mars penetrator the antenna, up-link transmitter and down-link receiver will be located in the afterbody, with the principal scientific payload, power supply and data handling electronics located in the forebody. Physical characteristics of the Mars Penetrator are listed in Table I.

Using the proposed entry system and decelerators, the penetrator impacts the surface with a nominal velocity of 150 M/sec and performs as follows:

- Penetrates to a depth of 1 meter in a low strength (2500N/cm^2 unconfined compressive strength) rock formation (this is typical of certain kinds of basaltic lava).
- The forebody penetrates to a maximum of 15 meters in soft material.

- The forebody payload experiences maximum average decelerations of 1200 earth g's for 15 to 20 millisecond and maximum peak decelerations of 1800 earth g's for 5 millisecond.
- The detachable afterbody experiences peak decelerations of 18000 earth g's for 2 to 3 millisecond.

Electronics Objectives. To fulfill the requirements of the Mars penetrator and the scientific experiments, the following electronics design objectives were established:

1. To support the scientific experiments with appropriate command and control, data gathering, data analysis, data storage, data transmission, and power.
2. To provide housekeeping information so that the states of health may be assessed for the scientific experiments and the electronics package itself.
3. To provide enough options in the command and control hardware to allow for a variety of situations.
4. To provide flexibility in the implementation of the command and control hardware. This flexibility is needed to make possible the inclusion of new aspects of the various scientific experiments as those experiments evolve toward their final designs.
5. To perform the above tasks during the variety of environments which the electronics package can be expected to experience.
6. To perform the above tasks for a long enough time to provide a scientifically useful mission lifetime (design goal: a lifetime of one earth year).
7. To perform the above tasks with enough reliability to provide a probability of success sufficient to justify the mission.

Command and Control and Telemetry. The command and control scheme for the electronics package has been designed specifically to address the first four points in the statement of objectives above.

First, in order to provide for the maximum flexibility in command, a command receiver has been included in the electronics package. The receiver allows an experimenter on Earth to change the operations of the scientific experiments through appropriate commands relayed to the penetrator via the orbiter. In order to insure that the proper command is executed,

the penetrator retransmits the command it receives and then waits for a specified time before continuing. This delay allows for any necessary correction (from the orbiter) of an incorrectly received command. In the case of the failure of the command link, the command and control logic on the penetrator will still step the scientific experiments through a preassigned sequence of operations. This facet of the command and control hardware thus provides a fail-safe operation in case the command link is somehow interrupted.

Data-gathering will be done digitally: analog signals will be digitized by an analog-to-digital converter which will be time-shared through a commandable multiplexer.

Data analysis, if such is desired by the experimenters, will be accomplished by the command and control logic, again with commands for analysis which will have been stored in the ROM. The control and computing capability of the onboard logic will be roughly comparable to that of a general-purpose 12-bit minicomputer.

Data storage will be accomplished through use of a 50-kilobit solid-state Random-Access-Memory (RAM). Use of such a memory allows storage of enough data to be compatible with the scientific missions which have thus far been designed, without using an inordinate amount of the necessarily limited power available in the penetrator. The random-access nature of the memory allows for great flexibility in data storage and allows for such possibilities as the easy addition of counts from the various frequency windows of the spectrum produced by the alpha-backscatter experiment as those counts are accumulated during successive time intervals.

Data transmission will be accomplished under command from the orbiter. Selection of the bit rate, time of transmission, and resetting of the penetrator clock from the orbiter master clock will be accomplished automatically. The data stored in the RAM will then be shifted out in sequence to the transmitter for transmission to the orbiter which will then store the data for retransmission to the earth at a lower rate.

Housekeeping information will be taken either under command from the Earth or at preassigned points in the operation of the scientific experiments, or both.

The third and fourth points in the statement of objectives are met by the fundamental principle of operation of the command and control portions of the penetrator: all commands are stored in a ROM. The appropriate sequence of commands is initiated from the ROM by having the command from the orbiter contain the address in the ROM in which the first command in the sequence is stored. By use of subroutines in the ROM an almost limitless number of different sequences can be initiated. Another virtue of the ROM is that the commands which actually control the commands to the experiments can be

easily altered as the experiments themselves evolve toward their final designs. (This “easy alteration” will be provided by using a programmable ROM until the final design.) Also, by altering the commands in the ROM, the operation of the whole system can be easily checked. After the final design of the system is complete, the storage of the commands in the ROM will make them secure by the nature of the virtual indestructibility of data stored in a ROM.

The design goals of appropriate hardening and reliability will be met by using proven hardware technologies which were developed for penetrators which were used in Southeast Asia.

The block diagram for the electronics is shown in Figure 3. The block diagram shows the division between the forebody, which penetrates below the surface, and the afterbody, which remains near the surface. The lines shown between the forebody and the afterbody constitute the umbilical that must be payed out between the two bodies.

The afterbody contains the transmitter and the receiver (necessary because the losses associated with carrying the radio-frequency signals down the long umbilical would be too great), the antenna and antenna deployer, some experiments and the logic to control them.

The forebody contains the command and control system, including the memories, the analog-to-digital converter (ADC) and the programmable multiplexer that feeds it; the power supply; and more experiments. Note that the power supply is composed of three parts: a battery (either a primary lithium system or a rechargeable nickel-cadmium system) between two Radio-isotopic Thermal Generators (RTG's). These RTG's supply 300 mw (electrical), and the 20 watts (thermal) will serve to keep the battery warm enough to operate. This power supply has been designed to meet the goal of a one year lifetime.

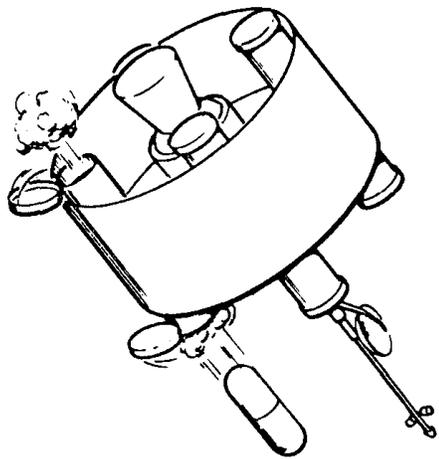
System Operation. A typical sequence of operation will begin with the emplacement of the penetrator in the ground. When the penetrator enters the Martian surface, the afterbody separates from the forebody and is emplaced at the surface to provide antenna support. The abrupt deceleration of the afterbody triggers a deceleration-sensing mechanism that releases the parachutes so that they will not interfere with antenna deployment.

As the forebody descends below the surface, the accelerometer generates a signal proportional to the deceleration. This signal is digitized and stored in the random access memory in the electronics package. After the forebody finally comes to rest and the deceleration signal has been safely stored in the memory, the penetrator command and control electronics issues the command to erect the antenna. Antenna erection must be accomplished immediately after the penetration to prevent the extreme cold (150 K) from hindering the movement of the mechanical parts.

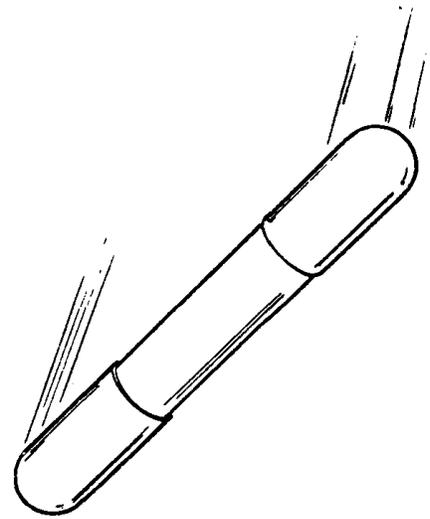
Housekeeping data will next be read. The penetrator will then transmit the acceleration and housekeeping data to the orbiter, which will analyze the Doppler shift in the signal from the penetrator to discover the penetrator location. Once the location of the penetrator has been determined, the orbiter can choose the optimum times for penetrator transmission. After the first transmission (barring command link failure), subsequent transmissions will be commanded from the orbiter at those optimum times. Also after the first automatic penetrator activities (erecting the antenna, reading the housekeeping information, transmission), the orbiter will command the specific operations to be performed by the penetrator. If the command link should fail, a “fail-safe” sequence of instructions stored in the ROM will be initiated. The “fail-safe” sequence will insure that at least some functions will be performed, but mission lifetime would be shortened in such an event. Mission lifetime would be shorter because the optimum time for transmission could not be selected and, therefore, the transmission period would have to be longer to insure that the orbiter would be able to receive the signal from the penetrator. These longer transmission periods would use up the energy available from the battery more quickly.

After the initial experiments are completed, the penetrators continue to fulfill their mission on Mars: measuring seismic activity and temperature and responding to commands from Earth via the orbiter. These commands can initiate such things as an adjustment of criteria for recording seismic events or the reperformance of the alpha-backscatter experiments. The penetrator mission thus provides a long-term assessment of Martian seismic activity and performs other measurements over an extended period of time.

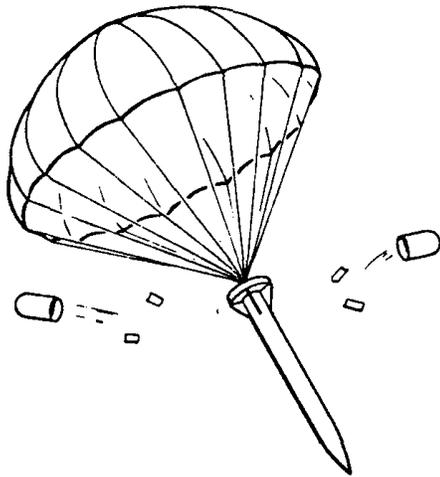
Conclusions. The method of exploring Mars by using surface penetrating vehicles offers certain advantages for scientific experiments, while being less costly than a soft lander. The design goals for such a mission present certain challenges for the design of an appropriate command and control and telemetry system. The challenges have been met by a design that utilizes a microprogrammable microprocessor and memory to provide the necessary flexibility and control, and by use of Radioisotopic Thermal Generators with batteries to supply the necessary long-term electrical energy and heat. Necessary criteria for hardness and reliability have been met through the use of proven penetrator electronics hardware technologies.



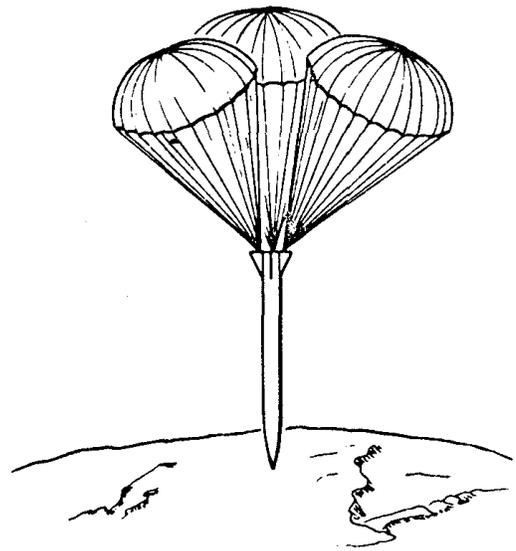
Canister Ejection



First-Stage Deceleration
(Canister Extended)



Second-Stage Deceleration
(Turnover Phase)



Third-Stage Deceleration
(Terminal Velocity Control)

FIGURE 1. ATMOSPHERIC ENTRY AND DECELERATION CONCEPT

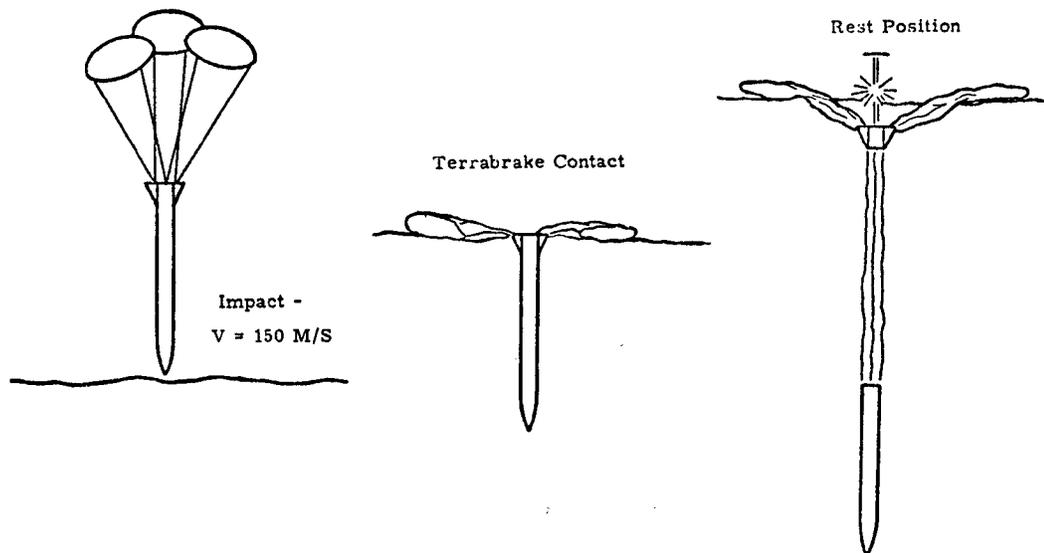


FIGURE 2. IMPLANT SEQUENCE

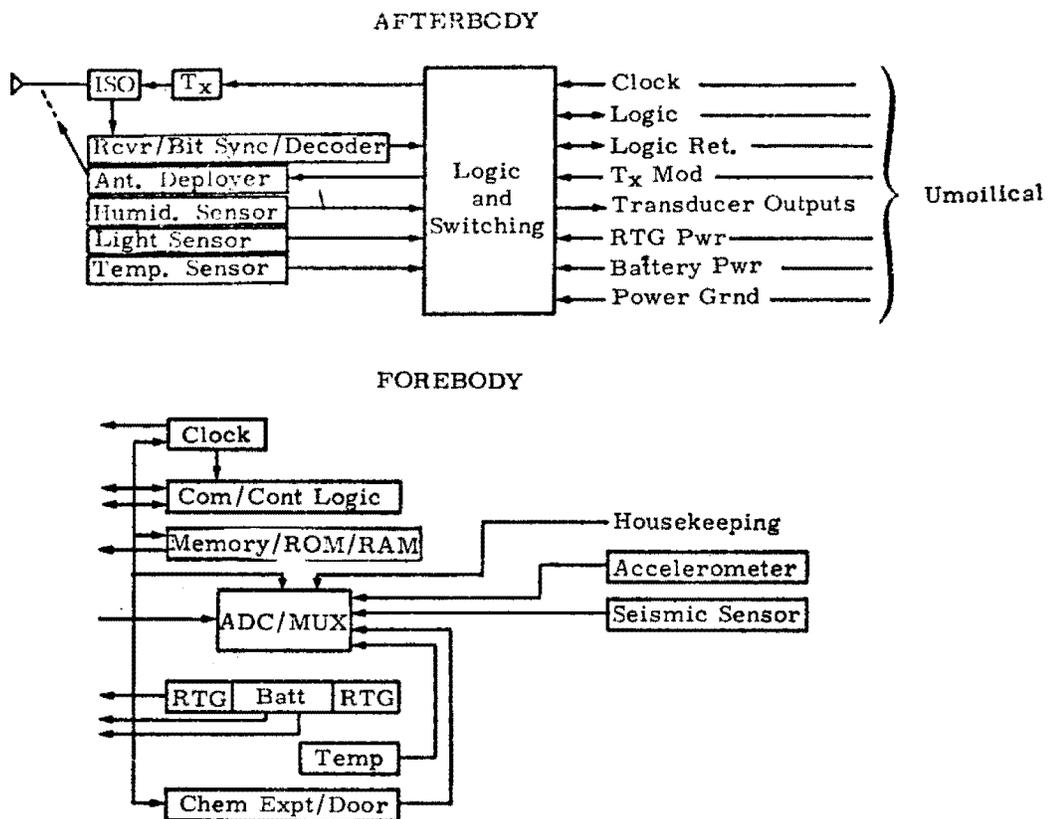


FIGURE 3. PENETRATOR ELECTRONICS BLOCK DIAGRAM

TABLE I

Physical Characteristics of Mars Penetrator

Complete Penetrator

Mass	31 kg
Principal diameter	9.0 cm
Frontal area	63.6 cm ²
Sectional density	0.49 kg/cm ²
Length	140 cm

Forebody Probe

Mass	28.7 kg
Principal diameter	9.0 cm
Frontal area	63.6 cm ²
Sectional density	0.45 kg/cm ²
Length	123 cm

Detachable Afterbody

Mass	2.3 kg
Principal diameter	23.0 cm
Frontal area	348 cm ²
Sectional density	0.007 kg/cm ²
Length	28 cm