SAND 96-2043C

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CONF-9609207--1

Integrated Reentry and Penetrator Vehicle (IRPV) for subsurface soil collection and analysis on Mars

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AUG 15 1996
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This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

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Integrated Reentry and Penetrator Vehicle (IRPV) for subsurface soil collection and analysis on Mars

a concept study
by

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Abstract

The continued exploration of Mars is a high priority item within NASA's interplanetary science community. It has long been a desire of this group to define an experiment that would investigate the possible presence and location of water/ice beneath the Martian surface. Until recently, however, there has not been a flight experiment dedicated to achieving this goal. This paper describes a concept design effort conducted at Sandia National Labs in collaboration with JPL and CalTech that has produced a feasible flight system to investigate this question.

Introduction

Sandia National Laboratories is a multi-disciplinary engineering organization operated for the Department of Energy in the mode of a Federally Funded Research and Development Center (FFRDC). Since its establishment over 40 years ago, its primary mission has been the development and maintenance of a safe and secure nuclear weapon stockpile. In addition to this mission, Sandia focuses a substantial amount of attention toward supporting other government agencies as well as the private sector in solving complex engineering challenges of national interest. A large majority of the over 8000 full-time employees hold advanced degrees in engineering, science and other related fields. Most of these employees are located at Sandia's principle facility in Albuquerque, New Mexico with the remainder operating from a facility in Livermore, California.

As part of its primary nuclear weapons mission and its growing support role for other federal agencies (especially the Department of Defense), Sandia has established an extensive capability to design, develop and test advanced aerospace systems. This responsibility is largely directed by the Aerospace Systems Development Center. During its 30 year history, this organization within Sandia has specialized in integrating aerospace vehicles designed to survive and operate in the extremely harsh environments (such as ICBM reentry and high performance penetrators). These tests are often intended to collect reliable data to assess the performance of the advanced vehicle design or as a proof-of-concept demonstration. These tests have been completed with an over 94% success rate on short time frames within well defined budgets. It is these types of technologies and capabilities that form the foundation of the Integrated Reentry and Penetrator Vehicle (IRPV) concept presented in the remaining sections of this paper.

Project Background

Sandia's previous interactions with NASA and JPL habe included a variety of space related programs. For example, Sandia's parachute group has had significant involvement with NASA flight system programs. These have included recovery systems design and development for all NASA Wallops sounding rocket payloads, the design of the space shuttle solid rocket booster recovery chutes, and the modification of the shuttle's landing brake parachute. More recently this group was also heavily involved in the design, fabrication and testing of the airbag landing system for the Mars Pathfinder mission. Other interactions have focused on applications of Sandia microelectronics systems (such as a hydrogen leak detector) and instrumentation capabilities to NASA program needs.

These types of on-going relationships led to an initial contact in 1994 regarding the possibility of an integrated reentry and penetrator vehicle to collect a subsurface soil sample on Mars. Although interest in this area has increased in recent years, this idea was initially investigated in the 1970s by Sandia at the request of NASA Ames. The results of that study (Ref. 1) using contemporary materials and decelerator technology produced a system design that was relatively complex and massive (a three stage decelerator with a total system weight of approximately 60 kg). Although this system concept is too massive to be considered for the present day application, this background and other recent interactions with NASA and JPL provided a solid foundation for a technical examination of this problem using Sandia's recognized expertise in reentry and penetrator systems described in the following section.

Applicable Sandia Technology Base

Reentry Systems

Sandia has designed, developed and flown over 100 Earth reentry objects in approximately 60 missions during the last 30 years. These include complex maneuvering reentry vehicles, light-weight yet highly instrumented bodies and several recovered reentry systems. Included in this group are some of the few reentry vehicles to use all carbon-carbon heatshield materials. In each of these flight tests, one of the principle objectives has been to measure and record a complete record of the flight data throughout very severe environments. This ability has facilitated decisions concerning the usefulness of advanced military systems and in many cases has provided extremely valuable data to the scientific community.

A variety of additional capabilities support the reentry systems program at Sandia. These include computer aided design and manufacturing efforts that have created the ability to rapidly prototype mechanical systems and components. A complete suite of ground test capabilities also exist to flight qualify mechanical and electrical components prior to the actual flight test or demonstration. Ground test equipment exists to vibrate, shock, accelerate and thermal cycle all flight components. The Aerospace Sciences group at Sandia also offers the ability to perform aerodynamic modeling, flight dynamic simulations (point mass, 6-DOF, etc.), aerothermal analyses, and decelerator design and testing.

Penetrators

Penetrator programs at Sandia span the spectrum of air delivered penetrators to monitor troop and supply movement along the Ho Chi Min trail in the Viet Nam war, ice penetrators to deliver scientific instruments and hard target penetrators developed rapidly and used effectively in Desert Storm. Sandia has conducted several thousand penetration tests over the past 35 years. More significant than the total number of tests is the scope of the experimental effort. On Figure 1 the vertical axis represents a target's resistance to penetration. Rock and concrete are near the bottom, and very soft soils are at the top. Penetrator weights have ranged from a few pounds to a few thousand pounds. The graphic symbols also represent tests where the penetrator was instrumented to record deceleration and other data. Penetrators have recently been successfully tested into concrete targets at striking velocities approaching the rigid body limit of approximately 4000 ft/sec.

To conductt such a large number of tests Sandia has developed specialized launch capabilities which provide exacting initial conditions for a range of weights (5 to 2000 lbs). Sandia maintains three mobile launchers: a 16" and 12" bore reacting mass (Davis) gun and a 6" bore compressed gas gun. In addition an aerial cable drop/pull down facility is located in Albuquerque, NM along with aircraft capabilities at the Tonopah, Nevada Test Range, and a variety of powder guns with various bore sizes in both New Mexico and Nevada.

Sandia maintains a penetration database which contains the most significant data through 1995 (Ref 2). This database stores all relevant impact and penetration parameters along with acceleration and strain data. For predictions of penetration performance along a strictly axial penetration path, Sandia utilizes empirical equations and finite element/difference codes (Ref 3). When there are lateral loads to consider, calculational capabilities are available for the kinematics (translational and rotational motion), trajectory, as well as penetrator damage/failure, and shock loads on the components within the penetrator (Ref 4).

Program Requirements

At the beginning of the concept study, basic mission parameters were defined in terms the delivery mechanism, sample collection depth and system mass and volume. A set of vehicle requirements were then derived from these mision parameters/goals to guide the concept definition and evaluation. The program goals and the derived design requirements are shown in the following table and the resulting design concept is presented in the next section of the paper.

Mission Parameters/Goals	Derived Requirement
Operate as a "piggy-back" experiment on the 1998 Mars Surveyor mission	Minimize mass and volume - original mass target was 20-30 kg - second iteration drove mass allocation to ~ 3-4 kg Minimize interface and interference with spacecraft - passive release Release on approach to Mars orbit - Velocity ~ 7.5 km/sec - Angle ~15 deg below horizon
Collect a soil sample from 1-3 m beneath the Martian surface	Penetrator performance - survive impact (design g levels) - impact conditions (V<200 m/sec, impact angle > 60 deg) - soil hardness (S#) Reentry system performance (ballistic coef, stability, etc.) Soil collection device
Transmit data to orbiting platform	Telemetry system performance - survive impact (design g-levels) - antenna system and power supply - insure transmission to orbiting platform

Concept Design

This section describes Sandia's conceptual design an Integrated Reentry and Penetrator Vehicle (IRPV) to collect a subsurface soil sample on Mars. This sample could be collected from a desired depth where the ice layer is predicted to exist (1-3 meters). As previously mentioned, the IRPV would be carried as an auxiliary experiment on an available Mars science mission and deployed on approach to the planet. The deployment mechanism, independent nature of the IRPV and the mission concept are remarkably similar to many ICBM (Inter-Continental Ballistic Missile) reentry systems in Sandia's experience base. The ballistic performance of the reentry system reduces the speed of the vehicle from its initial reentry velocity (~7.5 km/sec) to desired impact velocities of 100-200 m/sec. Impact velocity limits are dictated by penetrator survival, achievement of desired depth of penetration, and characteristics of the soil in the impact area.

The basic delivery and penetration scenario of the IRPV is illustrated in Figures 2 and 3. The reentry system depicted in these figures is largely constructed of light-weight carbon foam with a hard carbon shell created with a vapor deposition process. Sandia has experience using these carbon materials in several reentry programs and could readily apply this experience to the task of fabricating a strong, light-weight system that would survive the Mars reentry environment. Upon impact the penetrator housed in the IRPV slices through the nose of the vehicle and into the Martian soil. This delivery and release approach has been previously demonstrated on several Sandia developed Earth penetrator systems. Several concepts exist to facilitate collection of an in-depth soil sample for analysis to determine the presence of water/ice. One of the simplest of these would utilize a port in the nose of the penetrator that could be opened at a particular deceleration level to allow soil to pass into the inner analysis chamber. Another potential method would utilize a port that remains open constantly with a pass-through tube that allows the earliest soil entering the tube from the upper layers to pass completely through the penetrator body. The last remaining soil collected would then be obtained from the layers at depth as the penetrator comes to rest.

Figure 4 provides a preliminary concept for placement of instrumentation that might be housed within the penetrator body. The penetrator would incorporate miniaturized instruments that heat the collected soil sample and analyze any out-gassed products for the presence of water. A standard set of accelerometers would also be included in the penetrator to deduce the depth of penetration. This methodology has also been developed and reliably demonstrated in many Sandia penetrator tests. A recent plot of velocity and depth, calculated from the integrated acceleration trace from an air dropped penetrator, is shown in Figure 4.

A detachable after-body is designed for the aft end of the penetrator allowing the penetrating vehicle, containing all electronics except for the antenna, to penetrate to a depth as determined by the geology. When the after-body reaches the soil, it detaches, and stops at the soil surface. An umbilical line of sufficient length to cover a range of soil resistances connects the detached penetrator and its electronics to the after-body and antenna. All data collected from the penetrator would be communicated to the surface via a spool wire deployed during the penetration event (see Figure 3). A transmitter and antenna system would be left as the aft-body of the penetrator on or near the surface as the penetrator enters the Martian soil. This technique has also been demonstrated through previous Sandia weapon and sensor programs. Data would then be transmitted to an orbiting platform for relay to an Earth receiving station.

The power system, telemetry transmitter, accelerometers and other electronic systems required to survive this deceleration event have been developed and demonstrated throughout Sandia's extensive experience in other penetration projects. The major challenge of this proposed effort would be to miniaturize the sample analysis components and the other required electronic sub-systems to enable the complete penetrator to be as small and as light-weight as possible. Size and weight reductions would then translate directly into a reduced scale reentry system and could be accommodated on spacecraft envisioned for missions to Mars.

Preliminary Analysis & Test Results

During the definition phase of a preliminary concept, several types of analyses were conducted to validate the functionality of the design. Since studies conducted seveal years previously indictaed the need for a complex reentry and deceleration system, one of the most critical analyses for the current design study involved aerodynamic modeling and trajectory simluations to deteremine if a "simple", operational system system could be utilized. Drawing from Sandia's extensive background in reentry vehicle design and materials development, three basic shapes were examined as potential carrier vehicles for the penetrator housing the science experiments. These three basic shapes included a sharp nose radius cone, a blunt nose radius cone and a capsule shaped vehicle. The performance of these vehicles was assessed against the derived mission requirement to decelerate from orbital velocities to an impact condition that would be acceptable from a penetrator design performance standpoint (Ref 5). These initial parametric studies were completed for an assumed total vehicle weight of 10-30 kg using a point mass simulation code developed by Sandia (Ref 6).

Initial simulation results (shown in Figure 5) indicate that a simple blunt cone or capsule-like shape could be used to provide the proper deceleration performance. This would eliminate the complex, costly and heavy deceleration systems proposed for use in earlier Martian entry scenarios. Thermodynamic analyses also confirmed that these two vehicle types with the proper selction of materials could survive the thermal forces acting during Martian reentry (Ref. 7). Both carbon foam and shuttle-style FRCI heat shield materials were assessed during the theraml anslysis portion of the preliminary design activity for the bluint cone and capsule shape systems. Although both materials were shown to survive reentry heating, elevated back-face temperature were generated for the carbon foam heatshield on the blunt cone shape. This situation would require the potential addition of some insulating materials between the carbon foam and the penetrator body inside reentry vehicle. This arrangement is not unusual in several familiar reentry system designs. All of the above trajectory simulations and thermaml analyses were completed using the Mars GRAM atmosphere model (Ref 8).

Subsequent simulations and analyses focussed on the two issues: the aerodynamic stability of candidate configurations and the possibility of scaling down the mass of the entire system. Stability issues were a concern since the IRPV would likely be released from the Mars spacecraft on approach to the planet with little (if any) accomodation provided to preferientially orient the vehicle for reentry. High speed winds may also be encountered during reentry that could perturb the vehicle's orientation. These facts coupled with the requirements that the penetrator strike the Martian surface within relatively tight angle tolerance (AOA<5 deg) required that the vehicle meet static and dynamic stability constraints. A random reentry attitude was simulated by examining two extreme orientations: nose-laigned with the velocity vector and a broaside tumbling reentry. Simulations summarized in Figure 6 show that the blunt cone vehicle damps any initial angle of attack by approximately 40 km during the reentry. (static margin ??). Wind shear effects were also examined by applying fairly severe shear layers (V=100 m/sec) at low altitudes (Alt <10 km). The response of the blunt cone vehicle summarized in Figure 7 indicates that the vehicle would still recover from this type of momentary perturbation and damp the anlges of attack sufficiently to provide desirable impact angles for the penetrator.

Finally a set lower mass blunt cone simulations were completed to assess the potential performance of a downsized system. Since this can be accomplished by geometrically scaling the vehicle size with the proper mass reductions to maintain overall ballistic coefficient (beta=M/Cd*A), a down-sized vehicle was considered a good possibility. Simulation results shown in Figure 8 for 2,3, and 4 kg total mass confirmned this suspicion. The possibility of downsizing the complete IRPV is of course contingent on the ability of the science community to package the required instrumentation in corresponding less volume and reduced mass. Interactions with the responsible groups at JPL indicated that this was in fact achievable.

Sandia National Laboratories' 6" bore gas gun successfully conducted the initial investigation into penetrator geometries capable of penetrating several feet of an analog Mars target. These tests, conducted in February, 1995, were also used to assess the suitability of dynamic soil sampling with a penetrator and to measure the skin temperature rise of the penetrator during the penetration event. Figure 9 illustrates the gas gun prepared for one of the Mars penetrator test firings, and a penetrator with its attached sabot used to guide it down the gun barrel is shown in Figure 10. Presently, and as a result of this initial investigation, the Mars Surveyor Project is utilizing the 6" gas gun to evaluate a planned Mars penetrator probe. This testing has been and is presently being conducted at the Energetic Materials Research & Testing Center (EMRTC) located at New Mexico Tech., in Socorro, New Mexico

Summary

A preliminary design of an Integrated Reentry and Penetrator Vehicle capable of completing the Mars sample collection mission has been presented. The complete package is estimated to be approximately 12-14 inches long, 16-20 inches in diameter at the base, and weigh 3-5 kilograms. These estimates are preliminary and are strongly tied to the size and mass of the instruments to be carried within the penetrator for soil analysis. Not only does the IRPV concept design address a basic scientific need, but its development process also corresponds to a general philosophy emphasized within NASA's New Millenium Program (NMP). By connecting to a technology stream at Sandia developed for the Department of Energy and the Department of Defense, the NMP would be able to accomplish important interplanetary science experiments in a cost-effective manner. The current status of this enabling technology also indicates that this could be accomplished in a relatively low-risk manner.

The IRPV concept and associated technologies presented in this paper have the potential to provide the basic building blocks for a Mars network of soil samplers, seismic stations, and atmospheric monitoring units. Although this conceptual design effort only addressed the delivery of a single IRPV, additional technology exists at Sandia that would facilitate the reliable development, delivery and establishment of the network mentioned above. As a national laboratory, Sandia is committed to providing the NMP and others in the spaceflight community access to key technologies, personnel and capabilities that may be applicable to emerging national programs. It is our desire to remain an active part of the continuing effort to develop an "IRPV-like" concept in order to enhance the success of this bold and aggressive new program.

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Biographical Data for David L. Keese, Sandia National Laboratories

David Keese is currently the manager of the Rocket Systems Technology Department in the Aerospace Systems Development Center at Sandia National Laboratories. During his employment at Sandia, Mr. Keese has been involved in virtually all aspects of advanced aerospace vehicle analysis, design, development and flight testing. His experiences have included aerodynamic modeling of rocket and reentry systems, trajectory simulations to model the flight dynamics of these vehicles, and extensive interactions with test range personnel in connection with flight safety analyses. David's educational background includes graduate and undergraduate degrees from Texas A&M University in Aerospace Engineering. He also recently completed the Executive MBA program offered by the Anderson Graduate School at the University of New Mexico. Mr. Keese's interest in space activities led him to encourage the formation of an informal team of Sandians known as the Sandia Space Council. This group meets regularly to discuss common interests in space programs and to share information concerning new events and opportunities in this area. David also directed Sandia's early interactions with the Southwest Regional Spaceport to provide Sandia analysis expertise to support the initial feasibility study for a spaceport at the White Sands Missile Range.

Biographical Data for Ron W. Lundgren, Sandia National Laboratories

Ron Lundgren is currently a Senior Member of the Technical Staff in the Advanced Concepts & Penetrator Technology Department at Sandia National Laboratories. Ron's experience in penetrators spans a velocity regime of 100 to 5000'/sec and penetrator masses from a few pounds to several thousands pounds. He has served as project manager and actively participated in several hundred penetrator tests. His experience base for penetrator target geologies spans hard to soft in situ soils as well as rock, ice and frozen soils and man made targets such as concrete, wood and steel. Ron is experienced in the design and fabrication of penetrator systems including instrumentation, fuzing, and explosive components. Presently Ron is in charge of the three primary penetrator test devices: one 6" bore gas gun, and two reacting mass propellant Davis Guns (12" and 16" Bore). He has a BSME in Electromagnetics from the University of New Mexico.

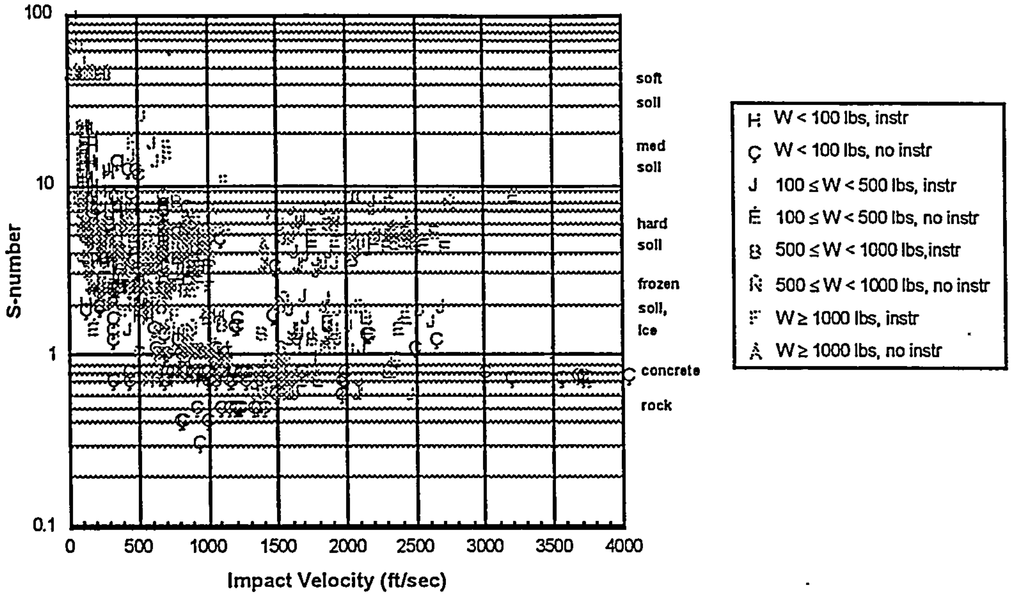


Figure 1

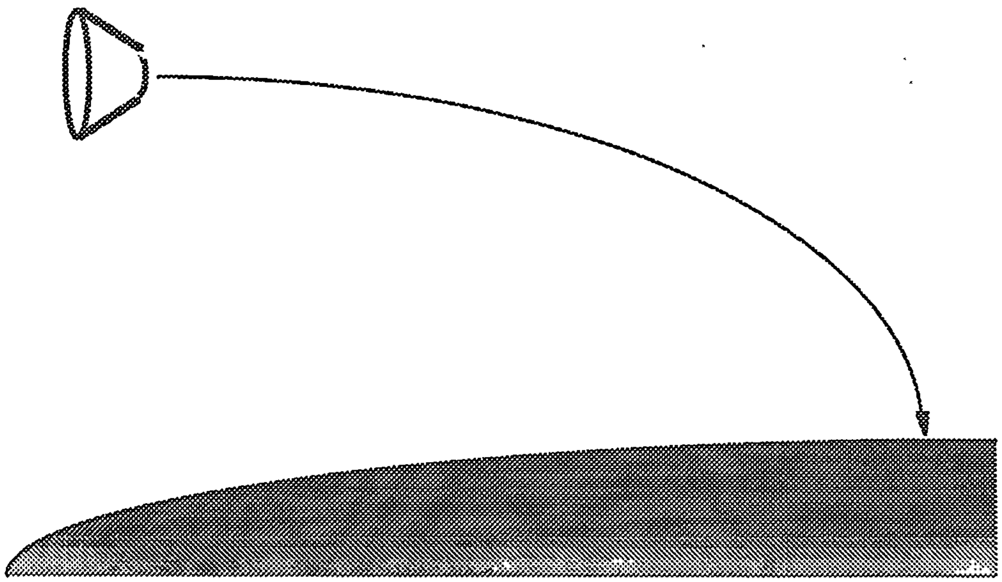


Figure 2

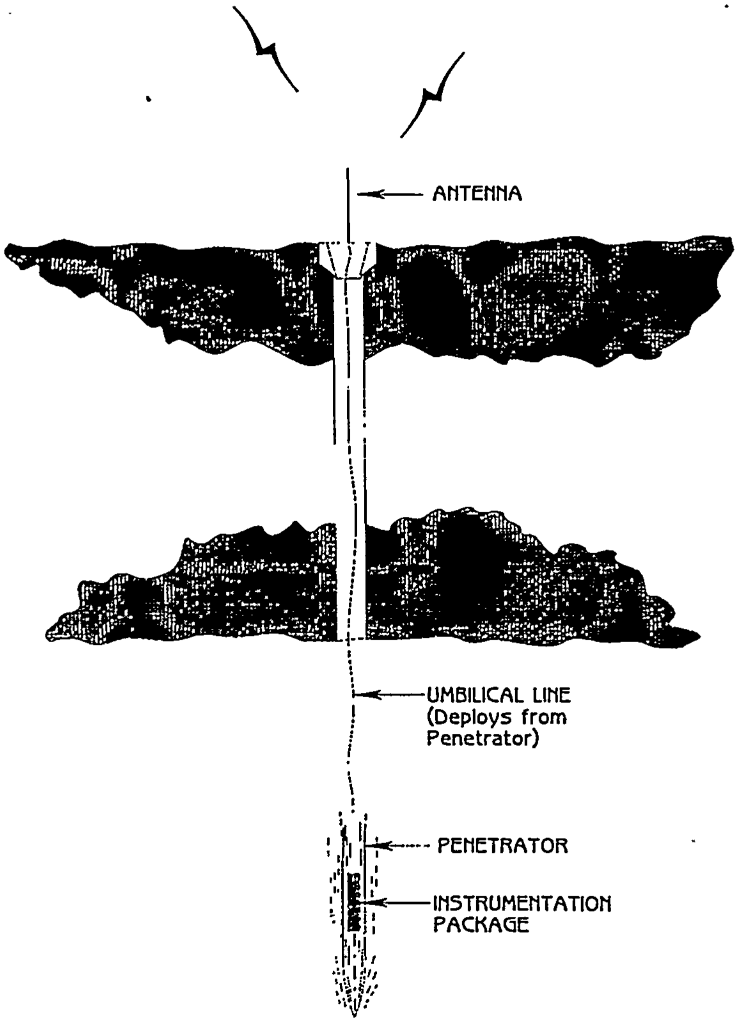

ANTENNA
UMBILICAL LINE
(Deploys from
Penetrator)
PENETRATOR
INSTRUMENTATION
PACKAGE

Figure 3

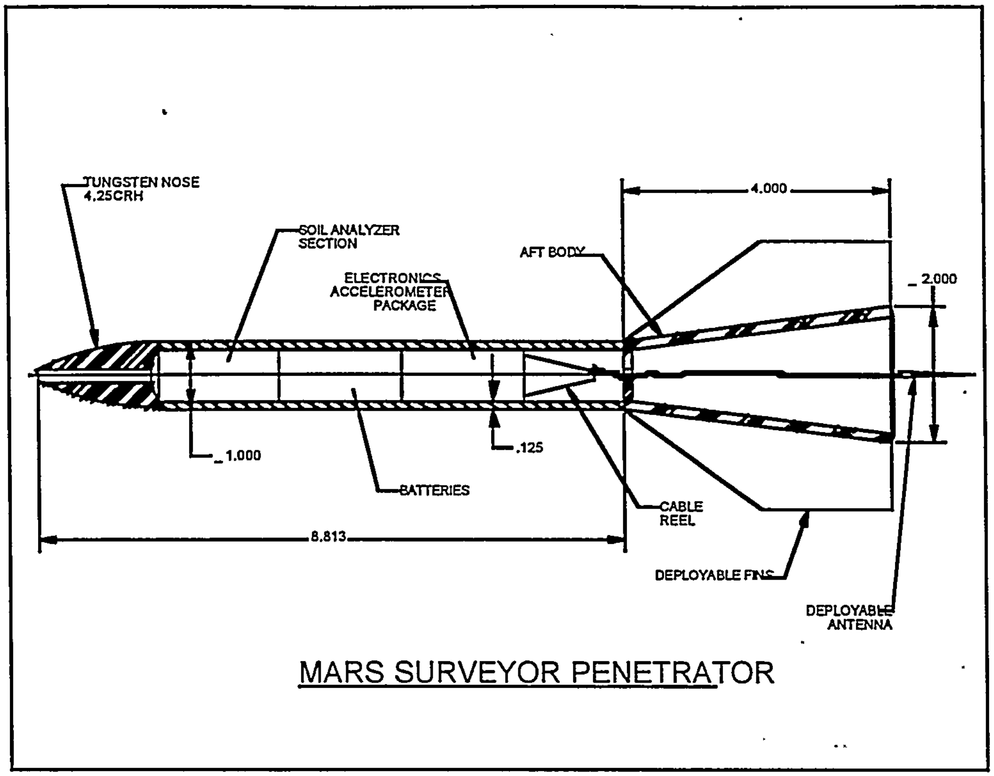


Figure 4

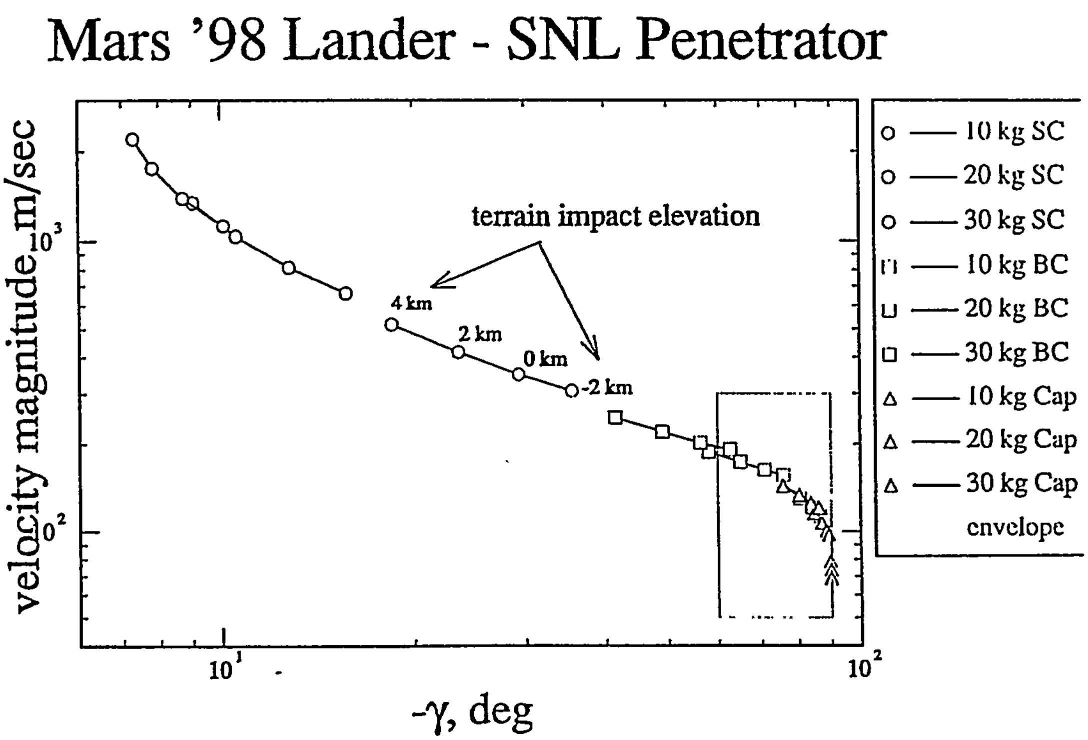


Figure 5

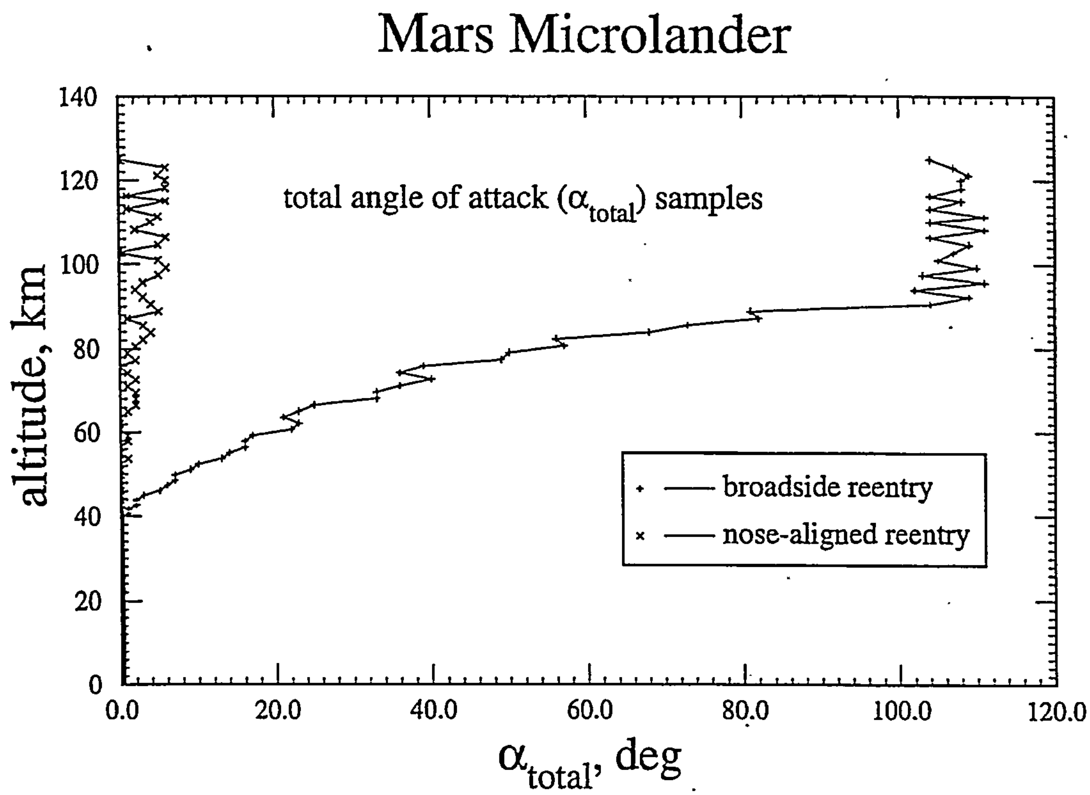
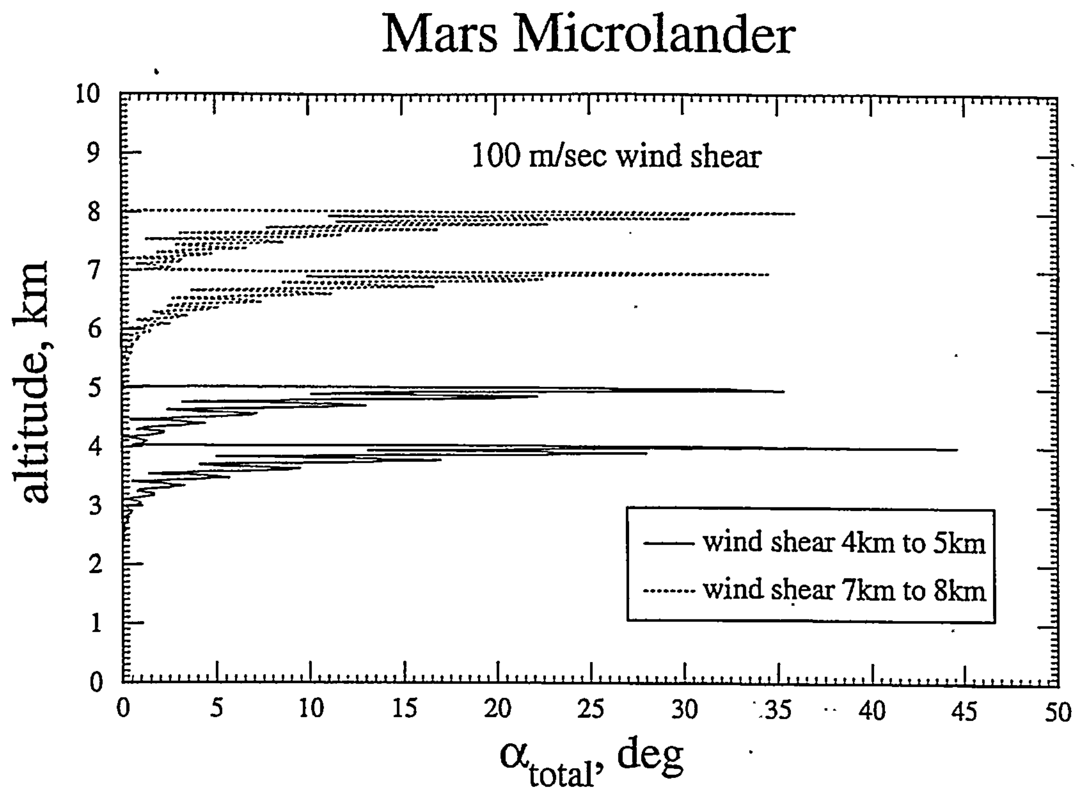

Mars Microlander
total angle of attack (α_total) samples
altitude, km
α_total, deg
broadside reentry
nose-aligned reentry
0
20
40
60
80
100
120
140
0.0
20.0
40.0
60.0
80.0
100.0
120.0

Figure 6


Mars Microlander
100 m/sec wind shear
wind shear 4km to 5km
wind shear 7km to 8km
altitude, km
α_{total}, deg
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
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25
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35
40
45
50

Figure 7

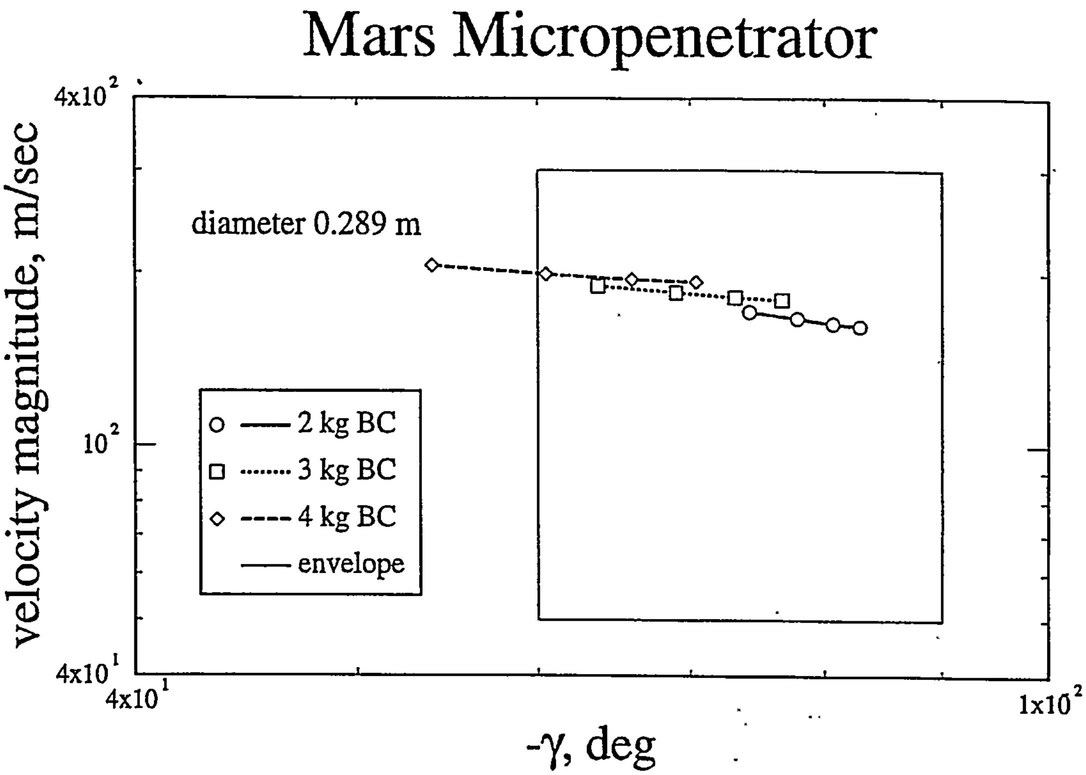

Figure 8

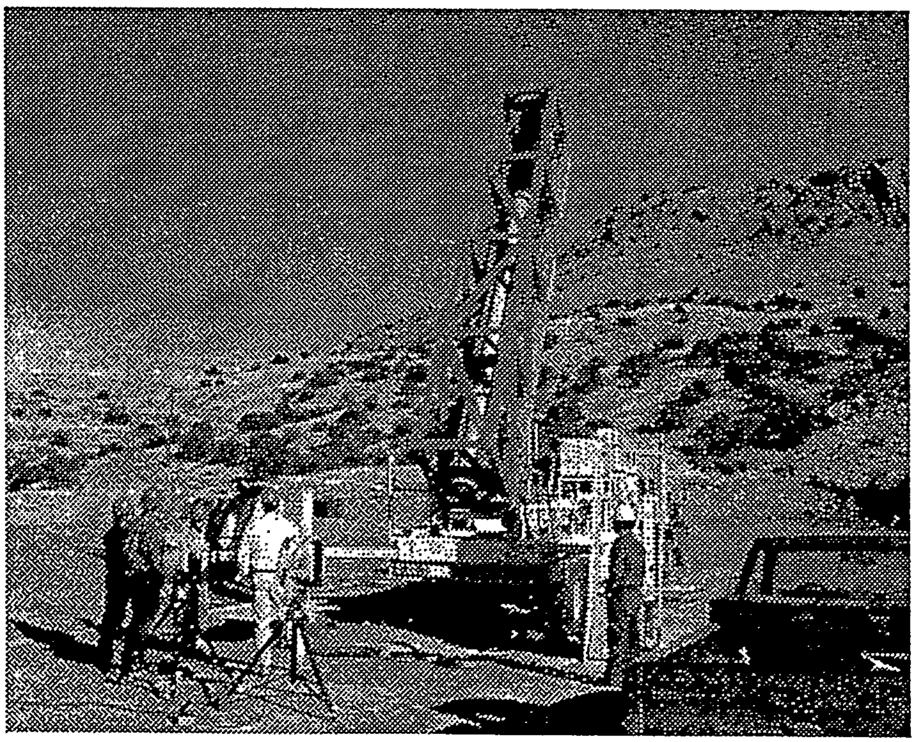

Figure 9

Figure 10