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James P. Murphy, Ray T. Reynolds,
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James P. Murphy
Ray T. Reynolds, Ames Research Center, Moffett Field, California
Maxwell B. Blanchard, National Waste Terminal Storage Program Office
Department of Energy, Columbus, Ohio
Uel S. Clanton, Johnson Space Center, Houston, Texas

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field California 94035

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James P. Murphy and Ray T. Reynolds

Ames Research Center

Maxwell B. Blanchard

National Waste Terminal Storage Program Office
Department of Energy

Uel S. Clanton

Johnson Space Center

SUMMARY

A number of scientific groups have recommended the use of surface penetrators for investigating the solid bodies of the solar system. Particular emphasis has been on the exploration of Mars, although NASA mission planning activities have proposed penetrators for missions to other solar system bodies.

This memorandum summarizes work on penetrators for planetary exploration that has been accomplished to date, either published or unpublished. In particular, it describes potential missions, including those to Mars, Mercury, the Galilean satellites, comets, and asteroids. A baseline penetrator design for the Mars mission is included, as well as potential instruments and their status in development.

Penetration tests in soft soil and basalt to study material eroded from the penetrator, changes in the structure, composition, and physical properties of the impacted soil, seismic coupling, and penetrator deflection caused by impacting rocks, are described.

Results of subsystem studies and tests are given for design of entry decelerators, high-g components, thermal control, data acquisition, and umbilical cable deployment.

INTRODUCTION

In 1974, the Space Science Board of the National Academy of Sciences recommended that surface penetrators[1] be considered as standard tools for exploration of the solar system (ref. 1). Prior to that recommendation and subsequently, a number of reports (refs. 2-24) have been issued on penetrator concepts for use on planetary bodies. In particular, the Mars Science Working Group (MSWG) (ref. 5) proposed that a 1984 mission consisting of an orbiter, penetrators, and rovers be the next logical step in the exploration of Mars. The penetrators were considered as key elements in achieving network science goals; however, the group identified several technical areas that needed additional investigation. These included further studies of wind effects during atmospheric entry, the probability of surviving impact in boulder-strewn fields, high-speed deployment of the umbilical cable, and the development of an adequate thermal system to permit the penetrator to survive a range of implant locations. Follow-on studies reported in this memorandum address those questions.

NASA for several years funded specific studies to investigate these and other potential problem areas in anticipation of a decision to proceed with hardware development. This technical memorandum is concerned primarily with reporting the results of NASA studies, and others supported by NASA, which were directed toward removing potential problems. Some of the studies have been published previously as Technical Memorandums, Contractor Reports, and Technical Papers, and some have been reported only in internal NASA documents. Most of the study effort on penetrators has now been terminated, since no near-term mission is contemplated. As a result, these diverse reports on work done previously may be lost because of limited distribution and lack of identity with a common project. Consequently, a major purpose of this Technical Memorandum is to provide, in a single publication, a summary of the work that has been accomplished for penetrator missions. To accomplish this objective, summaries of the principal previously reported studies are included, as well as previously unreported work.

SCIENCE

Science Rationale

Consideration of the penetrator concept by several different groups (refs. 5, 18, 20, 23, 24) led to the conclusion that penetrators are a necessary and feasible tool of planetary exploration.

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[1] Surface penetrators proposed for planetary exploration are elongated missile-shaped instrument carriers, weighing up to about 40 kg, which have been designed to implant scientific instruments below the planetary surface and to transmit the science data back to the launch spacecraft via a surface antenna connected to the buried penetrator by an umbilical cable. Figure 1 shows their development from military to space applications.

The Westphal Committee (ref. 18) found that the use of penetrators represented a low cost method of conducting certain essential in-situ experiments on many solid bodies in the solar system. They proposed that a minimum mission should consist of four penetrators, each carrying a seismometer, an imager, and at least one of the following: chemical analyzer, water analyzer, heat flow array, or meteorologic instrument.

The Terrestrial Bodies Science Working Group (TBSWG) (ref. 20) found that the exploration strategy for Mars between 1980-90 required four basic features: orbital science, network science, mobile-lab surface science, and sample return. TBSWG defined network science as geophysical measurements (e.g., seismic, heat flow, and meteorology) made over a relatively long time (1 year minimum) at several widely distributed locations over a planet's surface. Simultaneous measurements are required for seismic and meteorological experiments. The primary system proposed to accomplish the network science objectives was an array of 6-12 penetrators with science experiments covering seismology, magnetometry, heat flow, meteorology, surface imagery, geochemistry, and water detection.

The Mars Science Working Group (MSWG) (ref. 5) concluded that a 1984 Mars mission was the next step in the exploration of Mars with a sample return mission following at a future date (1990?). The proposed 1984 mission employed three types of vehicles: orbiter, penetrators, and rovers. The penetrators were considered key elements in achieving network science goals and were assigned the role of acquiring global seismic and meteorologic information with elemental and water-content measurements being highly desirable. The MSWG also identified several technical areas requiring more detailed study. These included further analysis of wind effects during atmospheric entry, the probability of surviving impact in boulder-strewn fields, high-speed deployment of the umbilical, and the development of a thermal control system to allow the penetrator to survive a range of latitudes and penetration depths. It should be noted that the studies summarized in this report address these issues and effectively demonstrate that wind, surface boulders, umbilicals, and thermal control system present no serious problem to the penetrator's survivability.

Penetrator missions have been studied for practically all of the solid planetary objects: Mercury (ref. 25), Mars (ref. 5), Comets (ref. 26), the Galilean satellites (ref. 25), and the Moon. Earth applications of penetrator systems have also been considered. In all these studies, it was shown that penetrators could provide fundamental scientific data and be technically feasible.

In summary, the value of a penetrator system in planetary exploration is recognized. A penetrator system would provide a modest cost exploration tool capable of providing information on the characteristics of the solid-body properties of a planet-chemical composition and internal structure. Without penetrators, this fundamental information must be obtained by very expensive soft landers or partially inferred from remote sensing measurements.

Science Experiments

As noted previously and described later in this report, a number of solar system penetrator missions have been studied and shown to be scientifically attractive; however, the most emphasis to date has been on the Mars mission. Consequently, the following discussion of experiments emphasizes science related to a Mars mission. Perturbations to the science selection for this mission would be necessary for other missions. For example, meteorology would have no value on an asteroid mission, and seismic studies, if any, would require active excitation. Nevertheless, the work accomplished for the Mars mission should be useful as a point of departure for all missions.

Network science experiments— Most of the science groups envisioned the primary role of the penetrator to be the gathering of global information about the planet's interior and atmosphere. For example, the Terrestrial Bodies Working Group (ref. 20) found network science to be one of the basic payloads needed for future exploration of Mars. They defined network science as measurements (e.g., seismic, meteorology, and magnetometry) made over a relatively long time (1 year minimum) at several widely distributed locations on the planet's surface. The following discussion of potential network experiments for a Mars mission is taken directly from NASA TMX-73,243 (ref. 27).

Seismology: While it may be possible to deduce some features of the interior structure of Mars from one seismometer and a very large Mars quake, a network of as many as 12 seismometers (ref. 21) at widely separated locations would accurately determine the interior structure of the planet.

As a natural consequence of the impact landing process of a penetrator, a seismometer will be well coupled to the Martian regolith. In contrast, the Viking II seismometer, mounted on the lander, is affected by vibrations induced by wind and thermal transients. Consequently, a high noise level can be present whenever meteorologic activity occurs. This problem is avoided if seismometers are emplaced beneath the surface with penetrators.

Meteorology: A global network of meteorological experiments is mandatory for understanding the seasonal variations in atmospheric processes. This network, consisting of experiments carried on the afterbody of a number of penetrators, can provide basic information on atmospheric circulation, the physics of important atmospheric processes, the nature of important small-scale local phenomena, and the observations of surface processes.

The essential measurements include pressure, temperature, and wind speed and direction. These measurements will permit the global atmospheric circulation processes to be defined. Estimates of transport rates also may be possible from a combination of these measurements and orbiter data. Other highly desirable measurements include relative humidity, atmospheric turbidity, and soil movement. Relative humidity will provide knowledge related to the seasonal and diurnal water cycle and the interaction of water with the regolith. The atmospheric turbidity measurements will assist in the interpretation of orbiter data on dust cloud formation and provide a means for determining the size, shape, and composition of suspended aerosols. Soil movement measurements will be used to study erosion rates and weathering processes.

Magnetometry: A network of magnetometers on the surface of Mars can provide information required to define magnetic fields and vectors and to differentiate between internally generated fields and those induced by the interaction of the ionosphere with the solar wind. While one magnetometer permits estimation of the properties of an assumed dipole field, several magnetometers when used with orbiting magnetometers permit offsets, inclinations, and deviations from a simple dipole to be determined. An internal dipole field, if present, can be described from these measurements, and models of the planet's interior electrical conductivity can be deduced.

Site characterization experiments— The principal advantage of the use of penetrators for site-characterization studies is the ability to study a large number of sites at a relatively modest expense compared to the use of soft landers on Mars by Vikings I and II. Mars exhibits a diverse assemblage of terrains. To sample these many different areas requires some technique for the wide dispersion of measurements, such as that offered by penetrators. Penetrators also permit sampling the surface below the windblown overburden material to provide knowledge of the crustal structure and composition leading to information on the evolution of the planet's surface. Five proposed experiments to be carried by penetrators for site characterization are geochemistry, water detection, heat flow, stratigraphy, and imagery. The following discussion of these potential experiments for a Mars mission is taken directly from NASA TMX 73,243 (ref. 27).

Geochemistry: The most important reasons for the study of subsurface chemistry are to obtain in-situ analysis of bedrock formations and to determine differences between surface and near-surface geochemistry. Both aeolian and impact cratering processes mix materials of the regolith. Chemical weathering also modifies the surface of the original crustal materials. The diversity of terrain types on Mars (cratered terrain, polar ice caps, young volcanic complexes, chaotic terrain, and laminated terrain) suggests considerable heterogeneity in minerals, and elemental composition should exist in some locations. It appears the crust is now covered by a well mixed and perhaps homogenized regolith, since similar bulk chemical compositions have been obtained at both Vikings I and II sites. It is, therefore, desirable to sample beneath the overburden in order to interpret the diversity of landforms observed on Mars and to gain an understanding of the geologic evolution of the planet. Penetrators are ideal for this purpose because they can penetrate beneath the surface of the wind-blown deposits and meteorite impact deposits and thus reach bedrock.

Water: A major aspect of Martian exploration is the search for evidence of life. The presence of water at a given site enhances the likelihood that the site is, or was, a habitat for life. The location of water is important for geological and geophysical reasons. For example, surface features observed in photographs taken by Mariner 9 and Viking Orbiter (ref. 24) suggest, but do not prove, that water flowed on the Martian surface at some time in the past, even though current Martian conditions are not favorable for liquid water. A major question concerns the amount of water stored in the regolith as permafrost and mineralogically bound water. Answers to these questions could clarify the origin of surface channels and provide clues to when an atmosphere existed and why conditions changed. Subsurface measurement of free and bound water is possible by emplacing water detection experiments beneath the surface with penetrators.

Heat flow: Martian heat flow measurements may be possible from penetrators. Since thermal gradients can vary widely over the planet's surface, it is desirable to measure these gradients in as many sites as possible to obtain meaningful planetary heat-flow values. The thermal inertia maps produced by the Viking infrared mapping radiometer will be essential to locate possible prime landing sites for heat-flow measurements. Because diurnal and seasonal temperature waves from the planet's surface interfere with thermal gradient measurements, these gradients should be measured as deep in the regolith as possible. Penetrators provide the only possibility of making heat-flow measurements beneath the influence of the diurnal and seasonal temperature waves. Heat-flow modeling studies (ref. 28) and laboratory experiments (ref. 29) show that planetary heat-flow measurements are feasible even though penetrators produce artificial thermal effects during the impact process. Of considerable value, as well, will be measurements of the thermal properties of the regolith materials.

Stratigraphy: Penetrators offer the only method for studying subsurface stratigraphy. It is certain that a major question for future exploration of the near-surface crustal structure of Mars will be how much have the aeolian and impact processes contributed to the production of the regolith (ref. 30)? The survival of crater ejecta blankets may provide clues on the roles of aeolian and impact processes forming the regolith on Mars. Each penetrator will carry an accelerometer that will allow the thickness of crater ejecta and wind-blown deposits to be deduced.

Many tests of penetrators impacting terrestrial materials have been performed (ref. 31) in which stratified deposits have been penetrated. The accelerometer records show a discontinuous change in deceleration occurs as the penetrator passes from one sediment type to another. These data indicated an obvious application to study near-surface stratigraphy of the Martian regolith. For example, if geochemical experiments detect bound water in clay minerals, then these measurements can be associated with changes in penetration resistance through interpretation of accelerometer records to verify different depositional environments.

Imagery: A camera on the afterbody of a penetrator can provide the opportunity to study the surface geology, the interaction between the surface and the atmosphere, and transient meteorological events. In addition, imagery can provide information on local morphology which can aid in interpreting the data from other experiments (e.g., seismometer, heat flow, geochemistry, stratigraphy). Imagery of surface terrain would be divided into near- and far-field observations. Near-field observations would include soil characterization (particle size, layering, weathered zone), cratering (areal density), aerolian processes (erosion), and condensates (H_2O and CO_2 ices). Far-field observation would include sit characterization, dust storm activity, and condensate cloud activity.

Science Instruments

The Westphal Committee (ref. 18) identified eight areas of interest for key scientific experiments for a Mars mission as: seismic activity, imaging, geochemistry, water measurements, heat flow, meteorology, magnetometry, and biochemistry. In all but meteorology, instrument studies have been conducted. Components intended to be located inside the penetrator forebody must withstand approximately 2,000 g and components in the afterbody, approximately 20,000 g.

The results of the instrument studies are reported in reference 19. A summary of the studies is given below.

Seismic experiment— Four preliminary designs of three-axis instruments were identified. All were based on transducers that measured displacement. The concepts included fluid viscous damping, resistance-bridge transducers, and a rigid caging system similar to the Viking seismometer with a limit stop for the test mass.

Imaging experiment— A camera using a 100 × 100 element CCD array was proposed for attachment to the afterbody to study soil characteristics, microcratering, aerolian processes, fog and frost, dust storms, site characterization, and determination of position and orientation of the afterbody by star observations. A Fairchild 100 × 100 array was subjected to 19,500 g perpendicular to the plane of the array with no damage to the array except for one open photogate attributed to other problems.

Geochemical experiments— Two types of geochemical experiments were investigated: the alpha, proton, and X-ray experiment, and the gamma-ray spectrometer. For the alpha instrument, four potential shock-critical components were identified. These were: solid-state semiconductor detector, alpha source, collimator and film, and Joule-Thomson cryostat. Of these four, two were tested. Shock testing of silicon detectors at 90° (in-plane) and at 45° angles were successful at 3,500 g. Cantilever-suspended collimators survived 3,500 g tests; however, the suspended films did not.

For the γ-ray spectrometer, a design based on the Apollo 15/16 was considered. A phototube (PMT)-scintillator was tested. Three 3-cm PMTs and three 3.5-cm PMTs were shock-tested. One of the larger PMTs collapsed when subjected to 3,500 g 12.4° off the central axis; all the other PMTs survived undamaged. A CsI scintillation crystal and a CdTe crystal were also successfully shock-tested.

Water detection experiment— Emphasis was placed on a P_2O_5 type of hygrometer. A commercial (Beckman) P_2O_5 electrolytic hygrometer sensor element was evaluated. Tests showed the sensor element responded to water vapor only in a Mars-type atmosphere and with sufficient sensitivity to function as a hygrometer in the Martian environment. Five sensors were tested and survived shocks up to 20,000 g.

Heat-flow experiment— The feasibility of making a heat-flow measurement from a penetrator in the Martian soil was examined mathematically. The studies showed the principal factors necessary for a successful Mars penetrator heat-flow measurement include substantial penetration (over 4 m preferably) and deployment of accurate temperature sensors (±0.05 K). No hardware was constructed.

Magnetometer experiment— A single-axis flux-gate sensor capable of performing onboard a penetrator was built and tested. The sensor was tested parallel and perpendicular to the direction of shock at levels up to 21,000 g. No sensor mechanical or electrical properties were affected.

Biological experiments— Experimental concepts were established. No hardware was tested.

Mission Concepts

Specific characteristics of a penetrator mission are dependent on the planetary body being investigated and the particular launch opportunity selected for the mission. Since no mission has been approved at this time, only general mission characteristics can be described.

Mars mission— NASA TM-73,243 (ref. 27) describes a Mars mission designed for the December 1983-January 1984 launch opportunity; Mars missions launched during other opportunities would be similar. In the described mission, each penetrator would be encased in a sterilized bioshield launch tube attached to the bus spacecraft. The bus spacecraft with penetrators would be launched by the Shuttle/IUS vehicle.

The bus spacecraft proposed is three-axis attitude controlled, and would be maneuvered at the time of penetrator separation to properly orient each penetrator launch tube in the direction required to impact the penetrator's target point on the planet's surface. At separation, the launch tube covers would be opened and the penetrator deployment motor fired. After separation, each penetrator would independently enter the atmosphere, decelerate, and impact the surface. At impact, the afterbody with surface instruments and communications antenna would remain on the surface as the penetrator forebody buried itself trailing the umbilical cable to the afterbody.

Specific studies of the atmospheric decelerator, umbilical deployment, effects of wind on impact and effects of striking boulders are covered in the latter portions of this memorandum.

Mercury mission— A report (ref. 25) by Science Applications, Inc. examined a penetrator mission to Mercury. A major difference in a Mercury mission as compared to the Mars mission is the lack of an atmosphere to decelerate the penetrator and control its impact attitude. Consequently, the SAI study examined a closed-loop retro-velocity system to slow the penetrator to a reasonable impact speed (≈150 m/sec) and an active attitude-control system for attitude control during retro and at surface impact. In essence, the deorbit system would bring the penetrator to zero velocity at an altitude above the surface of Mercury, so that the penetrator would then free-fall under Mercury's gravity to impact the surface vertically with the proper velocity.

Galilean satellite missions— The same SAI report (ref. 25) that examined the Mercury mission studied penetrator missions to the Galilean sat[illegible] (Io, Europa, Ganymede, and Callisto). Because of the lack of any [illegible] atmosphere on any of the satellites, the penetrator deployment mo[illegible] and ret[illegible] requirements are similar to those required for Mercury.

Comet missions— A Comet Nucleus Impact Probe feasibility study (ref. 26) was conducted by Martin Marietta Corporation for Ames Research Center. The study examined the impacting of three small penetrators into the nucleus of Comet Tempel 2. The penetrators would be launched from a Tempel 2 rendezvous spacecraft from a distance of about 10 km from the comet nucleus. Each probe would have a mass of about 1 kg, a diameter of about 3 cm, and a length of 40 cm, and would impact the nucleus at 50 to 75 m/sec. Three accelerometers and a temperature sensor would constitute the experiment instrumentation.

The penetrators would transmit impact deceleration and temperature data back to the launching spacecraft plus brief data samples every 5 min for an hour after impact.

Asteroid missions— Asteroid missions have been studied wherein penetrators could be placed into one or several asteroids on a single mission. Reference 32 describes six basic asteroid missions, including rendezvous missions capable of intercepting single large asteroids or multiple targets in the main asteroid belt.

Reference 33 also examines the use of penetrators for asteroid missions. Imagery and chemical information appear to be the most significant science for a penetrator. In particular, a detailed chemical analysis may be necessary to unequivocally answer questions about the relationships of asteroids to meteorites and the place of asteroids in theories of the formation of the solar system.

PENETRATOR SYSTEM DESIGN

The studies described in the latter portions of this memorandum were directed principally to the potential problems which surfaced during studies of a baseline design for a Mars penetrator. The baseline design described in NASA TM-73,243 (ref. 27) is summarized here as background information for the detailed studies given in the latter portion of this memorandum.

Launch Tube

Figure 2 shows the complete penetrator assembly in its launch tube. The weight and size of the assemblies are given in table 1. The launch tube houses the penetrator restraint system, electrical umbilicals, and the deployment rocket motor, and is hermetically sealed until deployment to permit sterilization. Rocket burnout occurs before the motor exits the container to reduce contamination of the bus spacecraft.

Decelerators

Two decelerator stages are used. The first-stage hypersonic decelerator consists of a large umbrella which unfolds after the penetrator exits the launch tube and, consequently, must withstand significant structural and thermal loads. The apex of the umbrella covers the penetrator nose and uses ablative material for heat protection.

The final decelerator stage controls impact conditions; in particular, it is designed to achieve impact velocities ranging from 135 m/sec to 165 m/sec and flightpath angles less than 10° from vertical. The proposed design uses a small drag plate of fabric to achieve these conditions. Because of residual questions regarding the baseline decelerator design, additional entry system studies were conducted and are covered in the latter part of this memorandum.

Penetrator

The basic penetrator design (fig. 3) is rocket-shaped with a blunted ogive nose and a conical flared aft section. The forebody is made of steel and the afterbody of aluminum. The penetrator is approximately 10 cm in diam and 140 cm long. When the penetrator forebody penetrates the surface, the afterbody separates and remains at the surface. The umbilical cable connecting forebody and afterbody is deployed from an umbilical storage area in the body. Questions on the ability of an umbilical design to meet the high-speed deployment led to the additional umbilical cable deployment studies reported in a latter part of this memorandum.

Penetrator Subsystems

The assembly shown in figure 3 meets the requirements for impact velocities of 135 to 165 m/sec and to withstand the resulting impact loads. The functions of experiment sequencing, power conditioning and control, commands, timekeeping, data collection, temporary storage, and formatting are accomplished by a microcomputer combined with a bubble memory.

Communication with the bus spacecraft requires a transmitter, receiver, and antenna mounted on the penetrator afterbody. The telemetry and command frequencies are both nominally at 400 MHz. The antenna is a quadrifilar helix with 3/4 wavelength elements wrapped for 3/4 turn. A telemetry rate of 2500 bps and a command rate of 800 bps are proposed.

Electrical power is supplied by a combination of Ni-Cad batteries and a small radioisotope thermoelectrical generator (RTG). The batteries are charged periodically by the RTG to provide the necessary power for the short peakloads during communication periods. Thermal control includes the use of the RTG as a heat source to keep the batteries at an operating temperature. The results of a thermal study are contained in a later part of this memorandum.

Design Modifications for Other Missions

Studies have been made of proposed missions which require major modifications to the baseline Mars penetrator described above. Such modifications include a much smaller and simplified version for a Comet mission (ref. 26) and a retro system for bodies without atmospheres (ref. 25).

PENETRATION STUDIES

Penetrators are designed to gather scientific data not only during the impact penetration period, but also in the buried state. Consequently, it is essential that the characteristics of the penetration and final resting position be understood if the mission and hardware are to be properly designed. To achieve this understanding, a series of test programs was conducted to examine various aspects of the penetration process. In particular, the following programs have been conducted in anticipation of a Mars mission:

- Penetration tests in loess and clay-silt sediments at McCook, Nebrasks (ref. 29).
- Penetration tests in basalt at Amboy, California (ref. 28).
- Penetrator deflection tests conducted at Tonopah, Nevada (ref. 34).

A summary of the purposes of these test programs and the results obtained follow.

Penetration Tests in Loess and Clay-Silt Sediments

Full-scale penetrators were dropped from an aircraft and 0.58-scale penetrators were embedded by an air gun into a test site at McCook, Nebraska. The site was selected to simulate penetration into wind-deposited sediments (silts and sands) on the Martian plains.

The objectives of the tests were to determine the amount of material eroded from the penetrator and deposited in the soil, and the changes in the structure, composition, and physical properties of the soil caused by penetrator emplacement.

Two full-scale Mars-type penetrators made of steel were air-dropped (fig. 4) from above 1500 m to achieve impact velocities of ≅130 m/sec, and two 0.58-scale models were emplaced by a trailer-mounted air gun (fig. 5) into a loess deposit at the test site. The penetrators and the surrounding soil samples were recovered for laboratory analyses.

As reported (ref. 29), the analyses showed mineralogical and elemental changes that were produced in the sediment next to the penetrators. Optical microscopy studies of material next to the surface of the penetrators revealed a layer of glassy material about 75 μm thick. Elemental analysis of a 0.1 mm layer of sediment next to the penetrators gave increased concentrations for Cr, Fe, Ni, Mo, and Na, and reduced concentrations for Mg, Al, Si, P, K, and Ca. The Cr, Fe, Ni, and Mo were in fragments abraded from the penetrator. Mineralogical changes occurring in the sediment next to the penetrator included the introduction of microsize grains of α-iron and several hydrated iron oxide minerals. Newly formed silicate minerals included metastable phases of silica (cristobalite, lechatellerite, and opal). The glassy material was mostly opal which formed when the host minerals (mica, calcite, and clay) decomposed.

In summary, field observations combined with laboratory analyses demonstrated that mineralogical and elemental changes are produced in the sediments next to the penetrator. Contaminants introduced by the penetrator occur as far away from the penetrator's surface as 2 mm. Although volatile elements do migrate and new minerals are formed during the destruction of the host minerals in the sediment, no changes were observed beyond the 2 mm distance.

These results indicate that some sample retrieval mechanism will be necessary to collect unmodified soils for geochemistry and water-detection experiments. A conceptual sample-acquisition system for a penetrator is illustrated in reference 33.

Penetration Tests in Basalt

Penetration tests were conducted at the Amboy laval field (fig. 6) in California. The test site was selected to simulate penetration into basalt flows on the Martian surface. Four full-scale penetrators were dropped from an aircraft; three impacted at 152 m/sec and one at 213 m/sec.

The principal objectives were again to determine the material eroded from the penetrators and the physical and chemical modifications in the basalt after impact.

Basalt samples were collected from areas near the surface of the buried penetrators (fig. 7) for laboratory analyses. As reported in reference 28, the analyses showed that mineralogical and chemical changes were produced in the powdered and crushed basalt immediately surrounding the penetrators. Optical microscopy studies next to the surface of the penetrators disclosed a layer, 0-2 mm thick, of glass and abraded iron alloy mixed with fractured mineral grains of basalt. Elemental analysis of this layer indicated increased concentrations of Fe, Cr, Ni, Mo, and Mn, and reduced concentrations of Mg, Al, Si, and Ca. The Fe, Cr, Ni, and Mo again were fragments abraded from the penetrator. Mineralogical changes occurring in the basalt next to the

penetrator included the introduction of microsize grains of α-iron, magnetite, and hematite. The newly formed silicate minerals included metastable phases of silica (tridymite and cristobalite). An increased concentration of Fe, Cr, Ni, and Mo occurred in the 2 mm to 1 cm layer for the penetrator that impacted at the highest velocity.

In summary, field observations combined with laboratory analyses have demonstrated that mineralogical and elemental changes are produced in the basalt powder next to the penetrator. Contaminants introduced by the penetrator occur as far away from the penetrator's surface as 1 cm and some new minerals are formed as the host minerals are crushed and melted. However, no changes were observed beyond the 1 cm boundary.

As in the penetration tests in loess and clay-silt sediments, these results indicate that some sample retrieval mechanism will be necessary to collect unmodified basaltic material for geochemistry and water-detection experiments.

Penetrator Deflection Tests

A series of 13 tests of 0.63-scale solid steel penetrators fired by an air gun (fig. 5) was performed at the Tonapah, Nevada test site to determine the deflection caused by impact with various sizes of volcanic rocks resting on or buried within compacted sediments.

The tests used prepared targets consisting of basalt from the Malpais lava flow in New Mexico. The basalt, a tholeiite having a porosity of 20 to 30%, was selected because of its similarity to Martian volcanic rock.

The targets consisted of three different arrangements of rocks buried beneath or laying on the homogeneous compacted dry playa sediments. One test series used layers of rocks buried 30 cm below the playa surface. Separate shots were conducted on 15 cm thick layers of 2- and 5-cm diam rocks and with single layers of 13-, 18-, and 61-cm diam rocks. Another series of tests consisted of penetrator impacts into single rocks (5-, 13-, 18-, and 61-cm in diam) lying on the playa surface. Another test consisted of impacts into layers of rocks lying on the surface. Separate shots were conducted for a 15-cm thick layer of cm diam rocks and single layers of 13- and 18-cm diam rocks. The rock layouts are illustrated in figure 8. In all tests, the penetrator was aimed at the half-radius of the target rock. The air gun produced penetrator impact velocities of 150 m/sec.

Final orientation of all penetrators was measured in-situ by means of a large access hole (fig. 9) drilled adjacent to the point of impact. Figure 10 shows the diagrams reconstructed from field measurements of three representative shots.

The conclusions derived from the tests as given in reference 34 are the following:

(1) Surface layers and buried layers of rocks which have diameters as large as 3 times the penetrator diameter cause only small (<10°) angles of deflection of the penetrator during its passage. Typically, single rocks at the surface cause greater deflections, and as the rock diameter increases, so does the final angle of deflection of the penetrator.

(2) Only large single rocks (>10 times the penetrator diameter) caused deflections appreciably greater than 10°.

In summary, the test results suggest that no catastrophic penetrator failure is likely to occur and that major deflections are caused only by rocks ≥10 times the diameter of the impacting body.

SEISMIC COUPLING TESTS

Seismic coupling experiments were conducted with half-scale models to determine the coupling of the Mars penetrator with the ground upon impact into fine-grained sediment and into volcanic rock. These two conditions were selected to represent anticipated Martian materials in which the penetrator would experience maximum and minimum penetration depths.

Tests for maximum penetration into fine-grained sediment were held at a dry lake bed site near Tonopah, Nevada. The minimum penetration tests into volcanic rock were conducted at White Sands Missile Range, New Mexico. The test program and test results are reported in detail in reference 30.

The degree of coupling for both test conditions was assessed by comparing vertical and horizontal seismic waves received by one geophone mounted on the embedded penetrator and another mounted directly into the undisturbed rocks or sediment. After each firing, a three-component geophone was mounted to the aft end of the penetrator with an adapter bracket. A three-component reference geophone assembly was then installed at a distance approximately 10 times the radius of the zone of disturbance caused by the penetrator. Several dummy penetrators were fired into the ground to generate seismic signals. The results of the tests in the two different ground conditions indicated that the penetrator-installed geophones were as well coupled to the ground as were the reference geophones over the frequency range of interest in earthquake seismology of about 3 Hz to 30 Hz. Some differences were observed at frequencies higher than 30 Hz. However, at these higher frequencies, local structural heterogeneities and resonances in the seismometer appear to be more important than possible decoupling of penetrators from the ground. Although these results from half-scale tests are encouraging, full-scale tests are required to evaluate the effects of a heavier full-scale penetrator which would generate a larger disturbed zone around its point of impact.

SUBSYSTEM STUDIES

The Mars penetrator subsystem studies included the following technical areas: atmospheric entry, penetrator integration on the Mars Geochemical Orbiter, high-g component survival, thermal control, data acquisition, and umbilical cable deployment. The first three studies were performed by Martin Marietta Corporation, thermal analyses by the Bendix Corporation, and data acquisition and umbilical cable studies by Ames Research Center.

Atmospheric Entry

The baseline entry configuration incorporates a deployable fabric and rib aeroshell which is erected after separation from the delivery spacecraft as shown in figure 11. The technical areas studied relating to penetrator entry are:

(1) Decelerator deployment and jettison techniques.

(2) Decelerator materials performance and structural deflection.

(3) Terminal descent phase.

(4) Effects of winds on angle of attack and impact conditions.

(5) Rigid decelerator option.

Decelerator deployment and jettisoning concepts— The objectives of this study were to evaluate concepts for deploying the penetrator entry decelerator after separation from the spacecraft and for jettisoning the decelerator from the penetrator prior to surface impact.

A. Deployment: Three deployment concepts were examined.

(1) Baseline sliding deployment strut.

(2) Extendable tube strut.

(3) Foldable strut.

Details of these studies are reported in reference 35.

The baseline deployment technique using a sliding collar to erect the struts could be improved by substitution of rolling collars to alleviate the potential stick or "hang-up" problem inherent in the sliding collar concept.

An extendable tube strut design incorporating a compressed spring located inside two concentric sliding tubes eliminates the need for sliding or rolling collars. However, this design results in the greatest overall decelerator weight (33.8 kg vs. 21.8 kg for the baseline) and extends the rear hinge line beyond the penetrator tail section in order to contain the telescoping tubes and springs.

The foldable strut concept having a strut hinged and folded at its center with a spring at each hinge point to provide the deployment force is a lightweight and relatively simple approach to decelerator deployment. However, this approach results in a larger package diameter than either of the other two concepts (43 cm vs. 30 cm for the baseline).

B. Jettisoning: Two jettisoning concepts were evaluated.

(1) Baseline jettison over the nose.

(2) Jettison over the tail.

Both approaches are shown in figure 12.

In the baseline over-the-nose approach, the decelerator is jettisoned by releasing a spring in the nose which thrusts the umbrella canopy forward, thus collapsing it. The momentum of this structure will supposedly pull the decelerator forward off the nose of the penetrator.

The alternate over-the-tail concept takes advantage of the large difference in ballistic coefficient between the penetrator and the deployed decelerator. The penetrator is dropped forward through the nose of the decelerator, allowing aerodynamic drag to strip the decelerator back and clear of the penetrator.

The over-the-nose approach appears marginal since it depends on the small difference in ballistic coefficients between the jettisoning decelerator and the trailing penetrator (37.7 kg/m^2 for the penetrator and second stage vs. 42.4 kg/m^2 for the collapsed decelerator) to accomplish separation. Jettisoning the penetrator forward through the nose of the decelerator provides a more positive separation technique with a slight increase in mass of ~3 kg and an increase in stowed diameter of 10 cm compared to the baseline method.

Decelerator materials performance and structural deflection— Objectives of this study were to evaluate technical problems associated with a fabric-covered decelerator and to examine possible decelerator deflections during entry loading.

A. Decelerator materials:

(1) Material selection. The criteria for the decelerator material were that it must be strong enough to withstand significant aerodynamic loading during entry at temperatures of at least 1370°C, must resist chemical attack by the hot boundary layer gases containing diatomic and monotomic oxygen, and must possess low flow-through characteristics that do not increase heating beyond acceptable limits. Because of these stringent requirements, a carbon fabric was chosen as the candidate material.

(2) Coated vs. uncoated fabric. There are advantages to be gained by coating the decelerator fabric with a flexible coating. Porosity of the fabric can be eliminated and a coating protects the load-bearing fabric from chemical attack by the atmosphere. If the coating can be ablated during entry, the temperature of the fabric can also be significantly lowered.

Problems associated with the use of coated fabrics include weight, bonding, and flexibility. A coating of teflon or silicone rubber, sufficient to protect the fabric through the entire heat pulse, would increase the total fabric system weight from 5.2 kg to 9.2 kg. This additional weight would make the fabric too heavy for the current deceleration design. Bonding of the coating to the fabric must be strong enough to prevent separation during entry while it is subjected to the heat pulse. And, finally, a candidate coating must be capable of withstanding a tight folding without significant damage.

Because of the uncertainty currently existing about coated fabrics, the feasibility of using the lighter weight uncoated fabrics was investigated.

(3) Carbon fabrics. Of a large number of carbon fabrics with widely varying properties found to be commercially available, six were selected and tested for their flow-through properties. Oxidation and high-temperature strength characteristics were obtained for these fabrics through a literature and vendor search (refs. 36, 37, 38, and 39). Oxidation, high-temperature strength and flow-through test data are given in reference 35. Based on these studies, an uncoated carbon fabric entry system appears feasible.

Graphite yarns are available with good strength to temperatures of 1370°C. Yarns free of alkali metals, which can catalyze carbon oxidation, are commercially available and appear suitably resistant to oxidation. Low flow-through fabrics do not increase heating beyond acceptable limits. Further testing is required on carbon fabric systems to completely characterize temperature, strength, weight, weight loss, oxidation rates, and flow-through factors critical to the final selection of a particular carbon material. Tests should include the determination of flow-through characteristics for heavier fabrics at more severe pressure ratios.

Although an uncoated fabric system appears feasible, the protection afforded by a coating warrants additional studies of coated carbon fabric systems. A system having only sufficient coating to afford protection through peak heating may be feasible and would be lighter and fold more easily than a fully coated system.

B. Decelerator deflection:

The foldable umbrella style entry decelerator provides a lightweight structure which can be folded into a compact cylindrical package around the penetrator body. However, this structure is relatively flexible and will deform under entry aerodynamic loads at elevated temperatures. A study by Menkes and Houbolt (ref. 40) showed that flexible cone structures may deform but tend to remain structurally stable.

Calculations also were made for the rib and fabric deflections under maximum entry dynamic pressure and aeroheating conditions to assess whether or not decelerator deflections were small compared to decelerator dimensions. Details of this analysis are presented in reference 35.

For an entry decelerator mass of 17.1 kg and a total penetrator system entry mass of 60.9 kg, it was calculated that the ribs and fabric panels of the decelerator resulted in only a small (≤3.5%) deflection of the cone structure. Such small deflections should not significantly degrade the flight dynamics or drag characteristics of the entry configuration.

Terminal descent phase— The baseline Mars penetrator system depends on an ambient pressure sensor to initiate staging from the entry configuration to the second-stage decelerator. This staging allows the penetrator to follow a descent velocity profile that assures surface impact within a velocity range of 135 m/sec to 165 m/sec for any surface altitude of -1 km to +10 km above the Mars Aeroid. The objectives of this study were to examine the feasibility of achieving the prescribed impact velocity conditions by utilizing a pressure-sensor staging initiator.

The ability of a pressure sensor to initiate staging within the required limits is dependent on the accuracy of the predicted atmospheric pressure. Atmospheric pressure on Mars is a function of the temperature, seasonal period, diurnal variations, and fluctuations imposed by regional atmospheric storms. Descent and landing site data obtained from the Vikings I and II spacecraft are the only currently available Martian meteorological information and, therefore, provided the basis for this study (refs. 41 and 42).

The results of this study indicate that the ability to specify the pressure value required for activating the staging sequence during any season, within ±0.5 km of the desired altitude of approximately 11 km, has not been shown. The reasons for this are:

(1) Vikings I and II descent data occurred geographically close together and essentially at one seasonal period;

(2) No major atmospheric variations (e.g., dust storm) occurred between Vikings I and II landings which have a significant effect on surface pressure and may alter pressures at the 11 km altitude; and

(3) No data are available on the seasonal vertical variation of temperature and pressure.

Prior to reaching a final conclusion on the use of a pressure sensor, it was recommended that further analysis of all available Mars meteorological data be made and a Martian atmospheric model incorporating and correlating all Viking measurements be developed.

Effects of winds on angle of attack and impact conditions— Past experience with the operation of earth penetrators has shown that the vehicle must impact the surface within a limited range of flightpath angle (angle between the velocity vector and the normal to the surface) and angle of attack (angle between the velocity vector and the penetrator longitudinal body axis) in order to attain satisfactory penetration.

Although the drag and stability characteristics of the penetrator will drive the flightpath and the angle of attack to zero near the surface, steady-state winds and sharp-edged wind shears could cause the penetrator to drift and/or oscillate, thus changing the flightpath angle and angle of attack.

A study was performed to evaluate the effects of both steady-state winds and wind shears on the Mars penetrator impact conditions using the wind profiles obtained from Vikings I and II during entry and descent to the Martian surface. Details of the study are contained in reference 35.

For the Viking Lander wind profiles, the study indicated that the penetrator could exceed the 5° angle-of-attack limit at impact by as much as 3° to 5°. Therefore, penetrator missions should be targeted from orbit instead of being released on direct approach to allow for an appropriate delay of entry in case of wind storms at the impact site on the surface of Mars.

Rigid entry decelerator option— The baseline penetrator entry decelerator system consists of a deployable rib and fabric structure which uses a high-temperature fabric material, such as graphite or carbon cloth. Because of technical uncertainties associated with the deployable decelerator concept that have not yet been fully investigated (e.g., strut deployment, fabric, etc.), a more conventional rigid aeroshell was studied using Viking structural technology.

A rigid aeroshell decelerator option was found not to be competitive with the deployable decelerator from either a mass or storage criteria. The mass of the rigid aeroshell comprised 45% of the total entry mass compared to 28% for the deployable decelerator. In addition, the rigid aeroshell diameter was 2.29 m compared to a diameter of 0.43 m for the deployable decelerator in the stowed condition.

For these reasons, the deployable fabric decelerator is the recommended approach for the Mars penetrator mission.

Mars Penetrator Integration on the Mars Geochemical Orbiter

The penetrator mission effectiveness depends on deploying a network of penetrators over the surface of Mars or target body. Because integration in a spacecraft of these penetrator units can affect spacecraft structure, equipment arrangements, thermal control, and deployment operations, a study was initiated to evaluate the problems associated with penetrator integration on the Mars Geochemical Orbiter (MGO).

Three methods were examined for integrating the penetrators with the MGO spacecraft. Depending upon the method selected, from 6 to 12 penetrators can be accommodated with a minimum of MGO hardware redesign and/or relocation. Details of the study are given in reference 35.

High-g Component Survival

A review of recent in-house programs conducted by Martin Marietta showed that cannon-launched guided projectile and earth penetrator programs have produced information relevant to the development of components capable of withstanding the high-g shock environment of the Mars penetrator. The environmental conditions associated with the various programs are listed in table 2.

Components have been designed, built, and tested to withstand high-g shock environments up to 30,000 g. Table 3 presents a summary of successfully tested components, their relationship to proposed Mars penetrator experiments, tested shock loads, and anticipated shock conditions on the Martian surface. Shock conditions are expected to vary between 2,000 and 20,000 g, depending upon the component's location in the penetrator.

Martin Marietta also conducted several penetrator tests into various target materials using impact velocities of 273-1099 m/sec. Pertinent data for these tests are given in table 4. All penetrators survived impact with little or no damage. Details of the component tests are given in reference 43.

Thermal Control

Studies conducted on the Mars penetrator design included:

(1) Thermal performance of the forebody at a depth of 15 m in steady state and transient modes;

(2) Thermal analysis of the afterbody and the determination of the radioisotope heater power required for thermal control;

(3) Thermal performance of the entire penetrator with the nose at 1 m depth; and

(4) A conceptual design for a variable conductance heat pipe.

Details of the studies are given in reference 44.

Forebody thermal analysis at 15 m depth— The forebody thermal model, shown in figure 13 was based upon the penetrator thermal model and included modeling of the surrounding soil, an estimate of the battery temperature with low- and high-soil conductivity values of 1.0×10^{-4} cal/sec cm °C and 3.0×10^{-4} cal/sec °C, respectively, and the presence of a variable conductance heat pipe. The effect of penetrator deployment at both equatorial and 60° latitude landing sites was considered.

Heating by a 10 W radioisotope thermoelectric generator (RTG) was found necessary to maintain NiCad batteries within the acceptable operating temperature range of -18°C to 52°C; however, the battery temperature operating range was exceeded in the steady-state conditions of low conductivity soil at the equator and high conductivity soil at a 60° latitude deployment. Forebody transient temperature analysis indicated that the 1 to 2 months necessary to reach a steady-state temperature for the low thermal conductivity soil still would permit sufficient time to conduct all of the experiments except those requiring extended observation time, such as seismic and meteorological measurements. The time for experiments to survive in high conductivity soil would be marginal.

The soil conductivity extremes used in the reported analyses may be in the low end of the conductivity range based upon recent studies of lunar and some Earth materials that could be representative of Mars soil. A thermal conductivity value of about 3×10^{-3} cal/sec cm °C could be a more reasonable upper bound representative of basalt sites on Mars.

If the higher thermal conductivity value must be satisfied, a design approach which thermally isolates the battery and instruments from the penetrator wall for the cold case could be developed.

Afterbody thermal analysis— The afterbody thermal model was formulated in a similar way to that used for the forebody. A thermal control concept using isolation between an inner and outer structure and a 10 W RTG unit was used to maintain battery operating temperatures within the required temperature range. Figure 14 shows the configuration of the components in the afterbody and the position of the radiator relative to the planet surface.

A model was prepared to select an appropriate size RTG unit to maintain a suitable temperature range for operating the electronics at equatorial and 60° latitude deployment and in Martian maximum daytime and minimum nighttime temperatures. The study indicated that a 10 W RTG thermal dissipation will maintain the components within the required range of -50°C to 70°C throughout the soil.

Penetrator thermal performance with the nose at 1 m depth— A thermal analysis of the complete penetrator embedded near the surface was performed. The high thermal conductivity soil value (3.0×10^{-4} cal/sec cm °C) was used as it is similar to hard rock conditions anticipated for a penetrator remaining near the Martian surface. The battery temperature response after deployment of the penetrator near the surface for both equatorial and 60° latitude was found to be similar to that obtained at the 15 m depth since at 1 m the penetrator is essentially in adiabatic soil conditions.

Variable conductance heat pipe— A design for a variable conductance heat pipe to control heat conduction from the penetrator into the soil was made. The design concept is shown in figure 15 with preliminary specifications given in reference 44. The heat pipe was mounted in the penetrator wall and connected to each instrument. The evaporator was connected to the battery/RTG interface. The effective resistance of the heat pipe was calculated to be 0.0083°C/W/in.

The following conclusions resulted from the penetrator thermal-analysis studies:

(1) Use a 10 W RTG unit and a variable-conductance heat pipe in the forebody;

(2) Use a 10 W RTG unit with thermal isolation of the inner structure and electronics in the afterbody;

(3) Meteorological temperature sensitive components should be mounted in the afterbody; and

(4) Thermally isolate the batteries and instruments within the penetrator forebody for high thermal conductive soils.

Data Acquisition

A seismic data acquisition method was developed for use on the Mars penetrator. In the system, data are gathered and stored as follows:

(1) Seismic data are monitored at frequencies up to 9 Hz;

(2) The 9 Hz data are stored in a continually updated 10-min buffer;

(3) Every third reading from the output of the 10-min buffer is stored in a 30-min buffer;

(4) Every third reading from the output of the 30-min buffer is stored in an 18-hr buffer.

At any given time, the penetrator data system will have 10 min of 9 Hz data, 30 min of 3 Hz data, and 18 hr of 1 Hz data. When the storage is completed, no new seismic data can be accepted until an orbiter command is received to transmit the data back to the orbiter. Transmission of seismic data only on command will prevent memory overload in the orbiter when data are available from the entire penetrator network. Once the event data are transmitted, another command from the orbiter instructs the penetrators to resume normal operation.

The memory budget for the revised data collection scheme is presented in table 5. Power consumption for the memory system during data acquisition remains the same as in the initial baseline design. Additional circuitry to allow seismic data to be collected during playback would require a small addition in power.

Umbilical Cable Tests

A critical element of the penetrator system is the umbilical cable which connects the instrumentation in the buried penetrator forebody to the afterbody at the planet's surface. This umbilical cable must deploy at a rate approaching the initial impact velocity of the penetrator, about 150 m/sec, after an afterbody shock of about 20,000 g. The cable may have to span a distance up to 12 m, and may contain 20 to 30 conductors. Cable storage is in the tail end of the penetrator forebody within a nominal diameter of about 8 cm. Figure 16 illustrates the deployment sequence. The most critical aspect of the umbilical design is the ability to deploy during the high-speed impact without breaking the cable.

A team at Ames Research Center[2] conducted a series of umbilical deployment tests to investigate the problems of deployment and to develop workable designs. The following discussion summarizes the designs and the results of the tests.

Test configurations— Figure 17 illustrates the test configuration which simulated the umbilical cable-deployment system. The cable is wrapped around a cylindrical mandrel from fore to aft in the umbilical chamber, with one end fixed to the afterbody and the other end to the forebody. As the cable leaves the forebody, it passes through a drag funnel. The drag funnel constrains the cable to reduce the high rotational motion acquired as the cable unwinds. By scrubbing against the funnel wall, the cable rotational motion is reduced, consequently reducing the twisting motion with its potential for breaking the cable.

The test cable selected was a beryllium-copper combination designated CD A172 which has a tensile strength of 175,000 psi. The wires which were 0.005 in. in diameter were formed into seven strand cables for the small model tests and combinations of seven of these cables to provide 49 conductors for the full-scale tests.

Test program— Tests were conducted using 1/2-scale and a full-scale model. The 1/2-scale model was used to establish cable stowage configurations, cable makeup, and mandrel/drag funnel combinations which then formed the basis for the design of the full-scale model.

Ames Research Center's 57 MM Smoothbore Gun Facility was used to launch 1/2-scale models at speeds of 150 m/sec, and the Ames Freeflight Facility was used for the full-scale tests. Figure 18 illustrates the test procedure for simulating cable deployment. The forebody and afterbody were joined by a light friction coupling. After being fired, the model passed through a plywood stripper which stopped the afterbody and allowed the forebody to proceed down range. After passing the stripper, the forebody flew through a vacuum chamber into a 55-gal drum full of cotton wadding. The vacuum chamber helped simulate the lesser aerodynamic damping from the Martian atmosphere. Figure 19 shows the range layout for the 1/2-scale body tests. Break wires were used to establish model speed with shadowgraphs and high-speed movies used to study cable deployment.

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[2] B. Gin, C. E. Barnes, T. N. Canning, R. W. King, and J. P. Murphy.

Results— The design for the 1/2-scale model was successful four times in five trials. The one failure was due to the stripper.

Additional changes were introduced into the full-scale model after a series of test shots. The most significant change was the inclusion of a polyurethane foam plug which filled the drag funnel. The plug reduces the initial shock on the cable at the start of deployment and subsequently is ground away by passage of the cable through the funnel. The final design was successful in four out of five trials. The failure was not with the cable, but with the afterbody mount.

The tests showed that with proper design, satisfactory cable deployment can be achieved at the required Mars penetrator impact velocities.

CONCLUSIONS

A number of scientific groups have recommended the use of surface penetrators for investigating the solid bodies of the solar system. Particular emphasis has been on the exploration of Mars, although NASA mission planning activities have proposed penetrators for missions to other solar system bodies.

Over a period of several years mission analyses, penetrator design studies, and surface penetration tests have been conducted in anticipation of a Mars mission. These studies indicate that the penetrator is well suited for both network science (seismology, meteorology, and magnetometry) and site-characterization (geochemistry, water analysis, heat flow, stratigraphy, and imagery) experiments at several widely separated locations on the planet's surface for relatively long periods. Also as a result of these studies and tests, a penetrator design has been established and penetration characteristics determined with no major technical problems.

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TABLE 1.- WEIGHT AND SIZES OF PENETRATOR SYSTEM ASSEMBLIES

Assemblies	Weight, kg	Size
Launch tube	7.5	29.2 cm diam × 234 cm long
Deployment motor	7.2	
Aero decelerator	16.5	
Penetrator with payload	37.9	10.5 cm diam × 140 cm long
Total	69.1	
Contingency	6.0	
Allowable system weight	75.1	

TABLE 2.- SUMMARY OF MARTIN MARIETTA PROGRAMS

Program	System description	Environmental condition
Copperhead	Guided projectile fired from 155 mm cannons	9,000 g shock impact at base of projectile w/amplification up to 30,000 g
Navy guided projectile	Guided projectile fired from 5 in. or 8 in. guns	7,500 g shock impact at base of projectile w/amplification up to 30,000 g
Pershing	Reentry earth penetrator vehicle	Sand to rock with impact velocity of 457-914 m/sec
	Kinetic energy runway penetrator	Concrete 3.49×10^6 kg/m^2 with impact velocity of 244-457 m/sec
	Dual mode penetrators	Sand to concrete 3.49×10^5 kg/m^2 with impact velocity of 244-457 m/sec

TABLE 3.- SUMMARY OF COMPONENT SHOCK-TEST DATA

Mars penetrator experiment	Components/ hardware	Shock requirement, g	Program	Component	Shock environment, g
Seismic	Biaxial bubble tiltmeter	2,000	Ames Research Center	Plans to test in the future	N/A
	Force balance accelerometer	2,000	Ames Research Center		
Magnetometry	Triaxial fluxgate magnetometer	20,000	Copperhead (AD)	Ferromagnetic core device	10,000
Meteorology	Thermocouple	20,000	Copperhead (AD)	Thermocouple	10,000
	Pressure sensor	20,000		Endevco commercial parts	20,000
Stratigraphy	Accelerometer	2,000	Copperhead (AD)	Endevco commercial parts	10,000
			Navy guided projectile		100,000
Camera	Imager	20,000	Ames Research Center	Fairchild 100 × 100 CCD	19,500
			Copperhead (AD)	Plastic lens and electronic parts	10,000
			Navy guided projectile	Silicon wafer and ceramic rings	30.000

TABLE 3.- Concluded.

Mars penetrator experiment	Components/ hardware	Shock requirement, g	Program	Component	Shock environment, g
Telemetry	Receiver	20,000	Copperhead (AD)	Diodes Semiconductors Capacitors Resistors Coil	10,000
Telemetry	Transmitter	20,000	Copperhead (AD)	Transmitters Capacitors Diodes Resistors Coils	10,000
	Antenna	20,000			
Data processing and control	Memory	2,000	Copperhead (AD)	Integrated circuit	10,000
	Microprocessor (12-bit CMOS integrated circuits)	2,000	Copperhead (AD)	CMOS integrated Mark Pak I & II	10,000
			Navy guided projectile		30.000
Power source	Battery	2,000	Copperhead (AD)	Thermal battery Ni-Cad battery	9,300
Heat flow	Thermocouple	2,000	Copperhead (AD)	Thermocouples	10,000
	Unbilical cable	20,000	?	?	?

TABLE 4.- SUMMARY OF MARTIN MARIETTA PENETRATOR STUDIES

Title	Target material	Angle of attack, deg		Velocity range, m/sec
		Lower limit	Upper limit	
Kinetic energy runway penetrator tests	Concrete	0	20	331-460
Super X hydrostone fiberglass target tests	Super X hydrostone fiberglass target	0	3	273-724
Hydrostone-fiberglass target tests	Hydrostone-fiberglass target	0	3	374-1,099

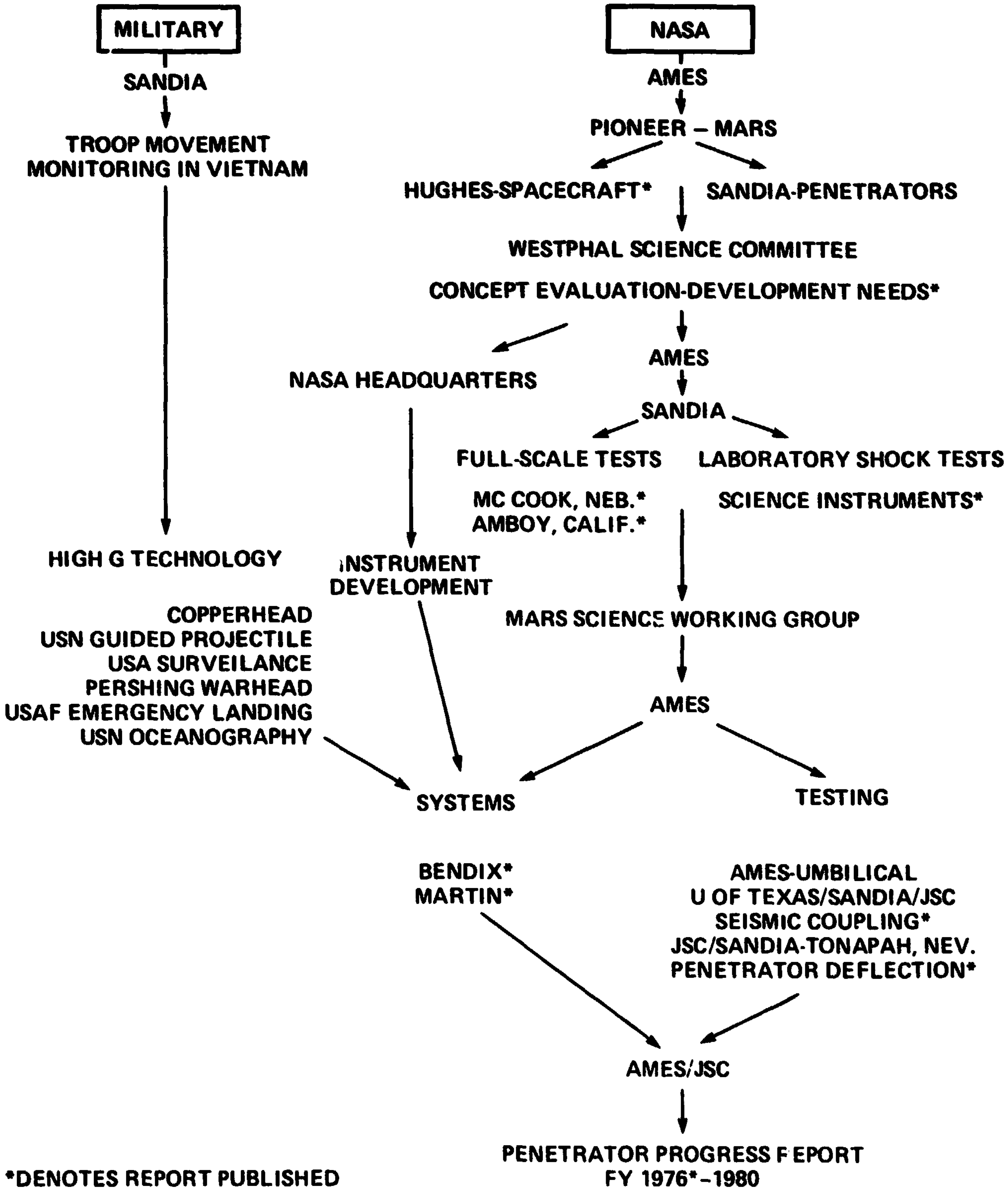


Figure 1.- Penetrator development.

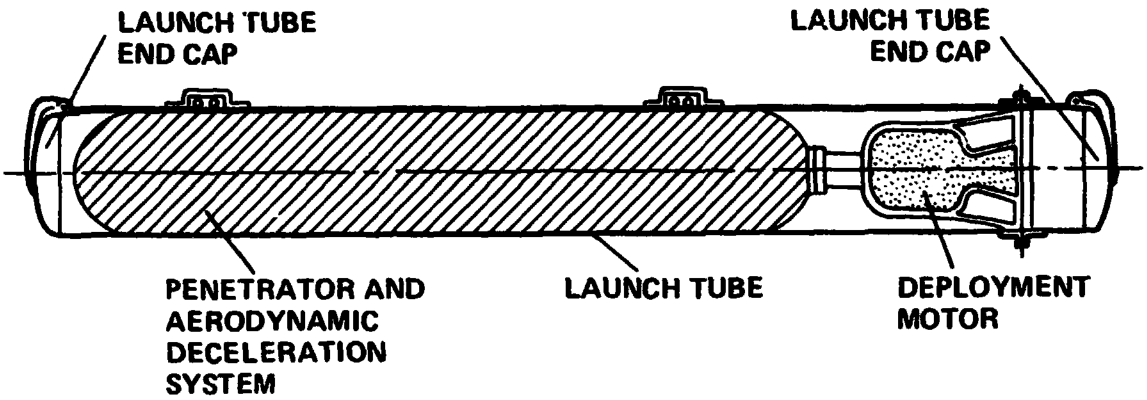
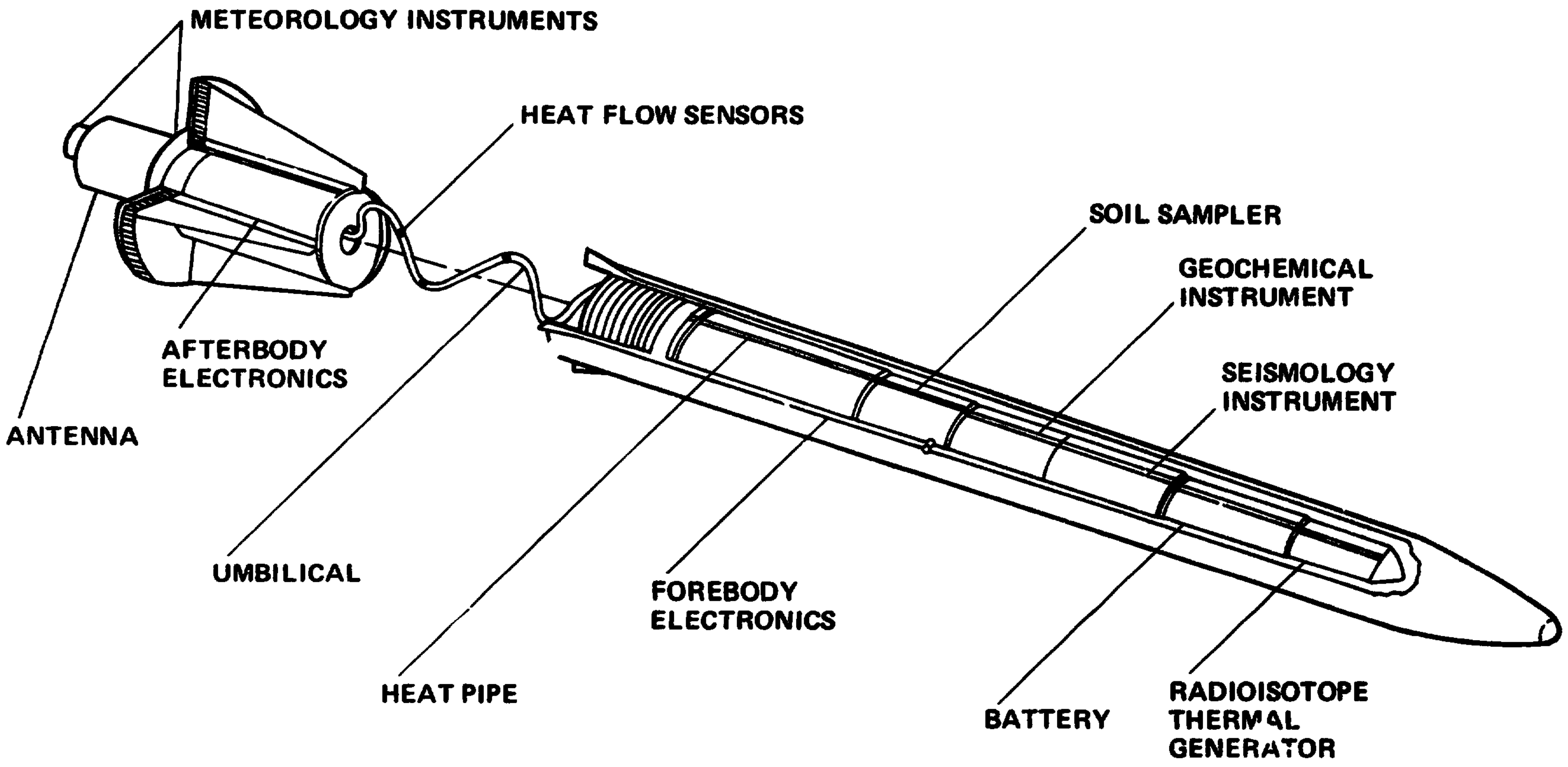


Figure 2.- Penetrator assembly in launch tube.



AFTERBODY HAS BEEN SEPARATED IN ABOVE VIEW FOR CLARITY

Figure 3.- Mars penetrator.

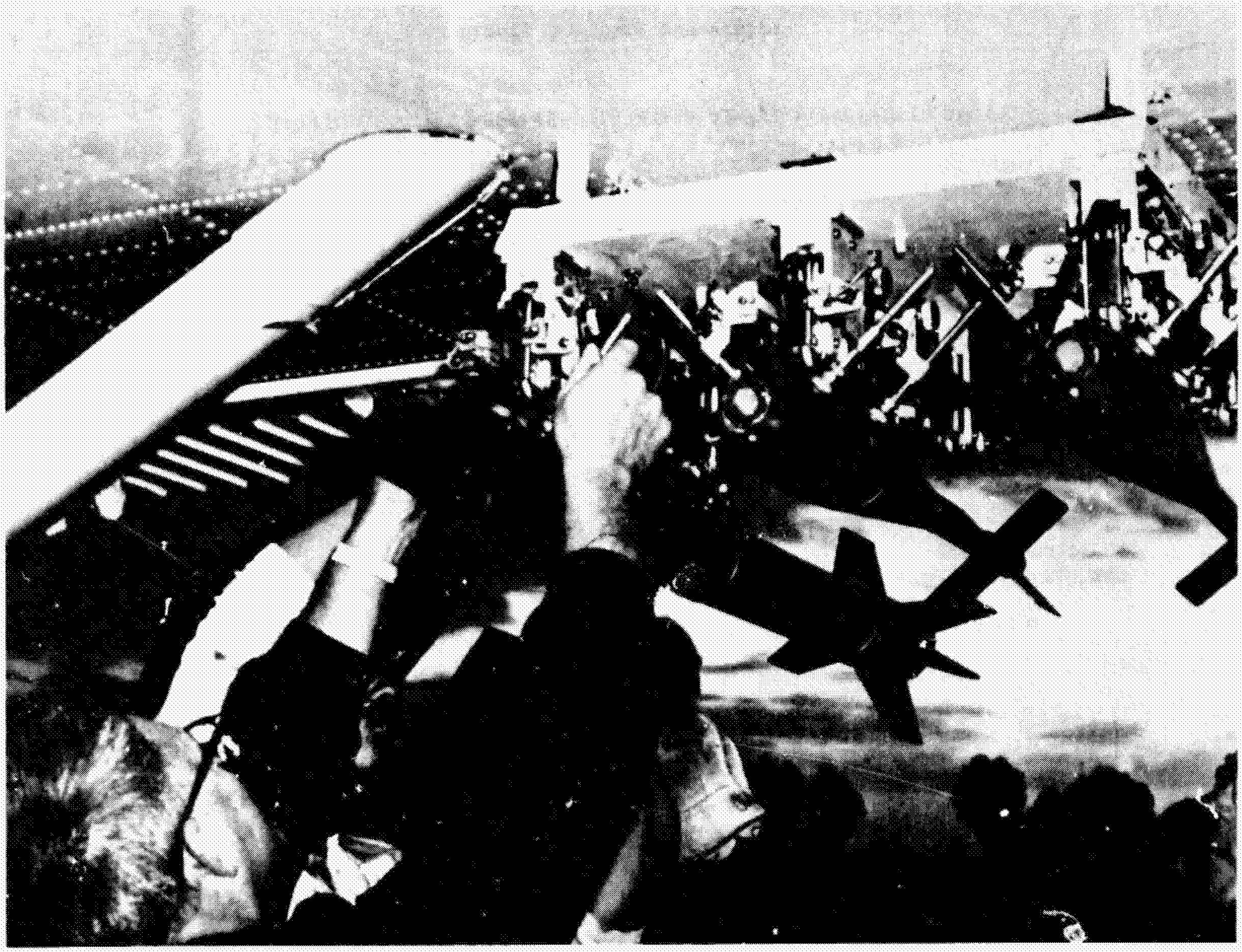


Figure 4.- Penetrator and two smoke bombs mounted under the wing of an aircraft before drop tests.

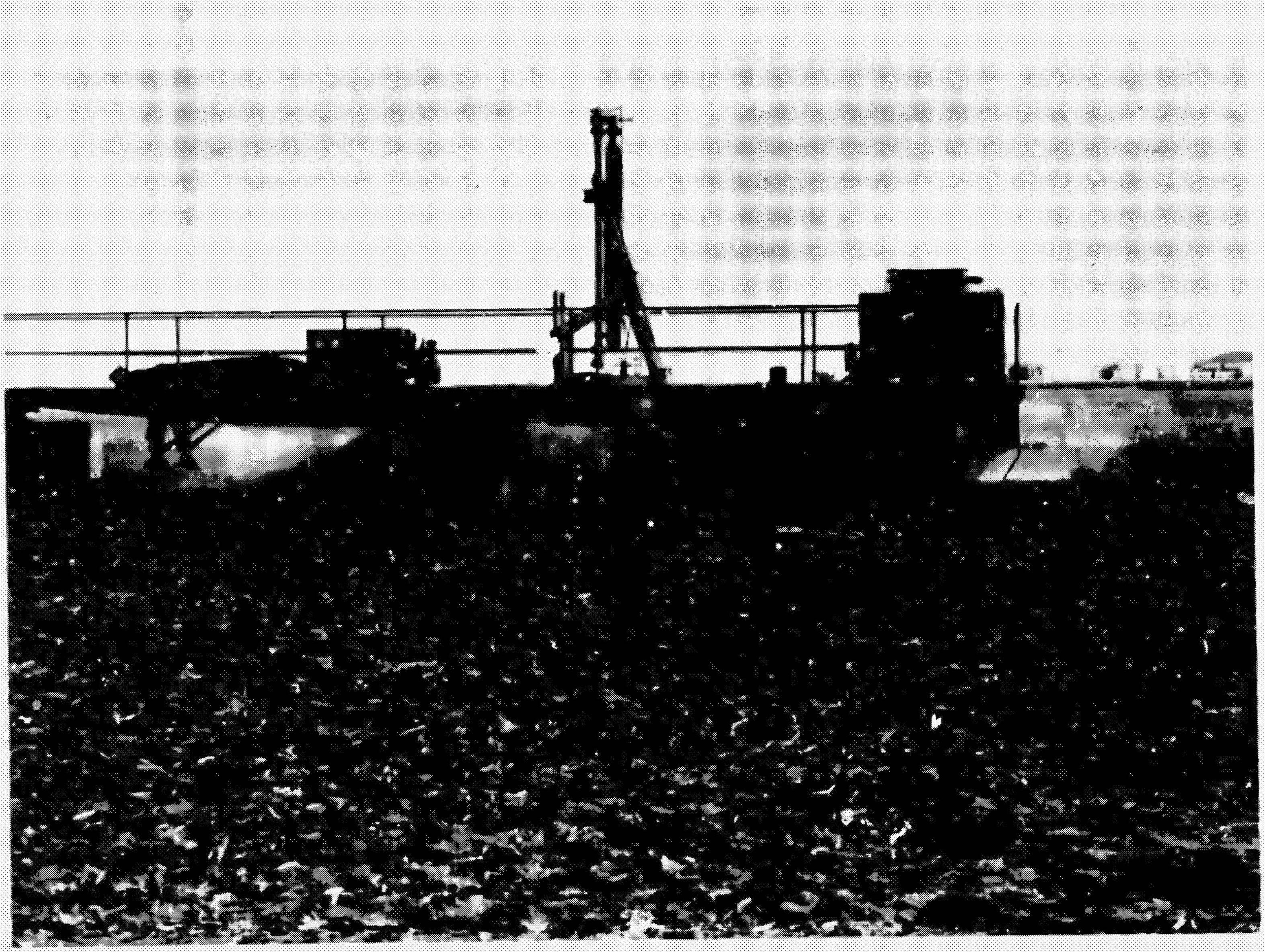


Figure 5.- Test firing from trailer-mounted air gun of 0.58-scale penetrator into layered clays and silts a few feet away from landing site of air-dropped full scale penetrator.

Figure 6.- Oblique aerial view of Amboy Crater and surrounding lava field. Jeep track at bottom of picture crosses the plateau used as the test site. (Photo courtesy of R. Greeley, University of Santa Clara.)

Figure 7.- Radial fractures were produced by the penetrator during emplacement in the basalt; they were revealed when the alluvial overburden was removed.

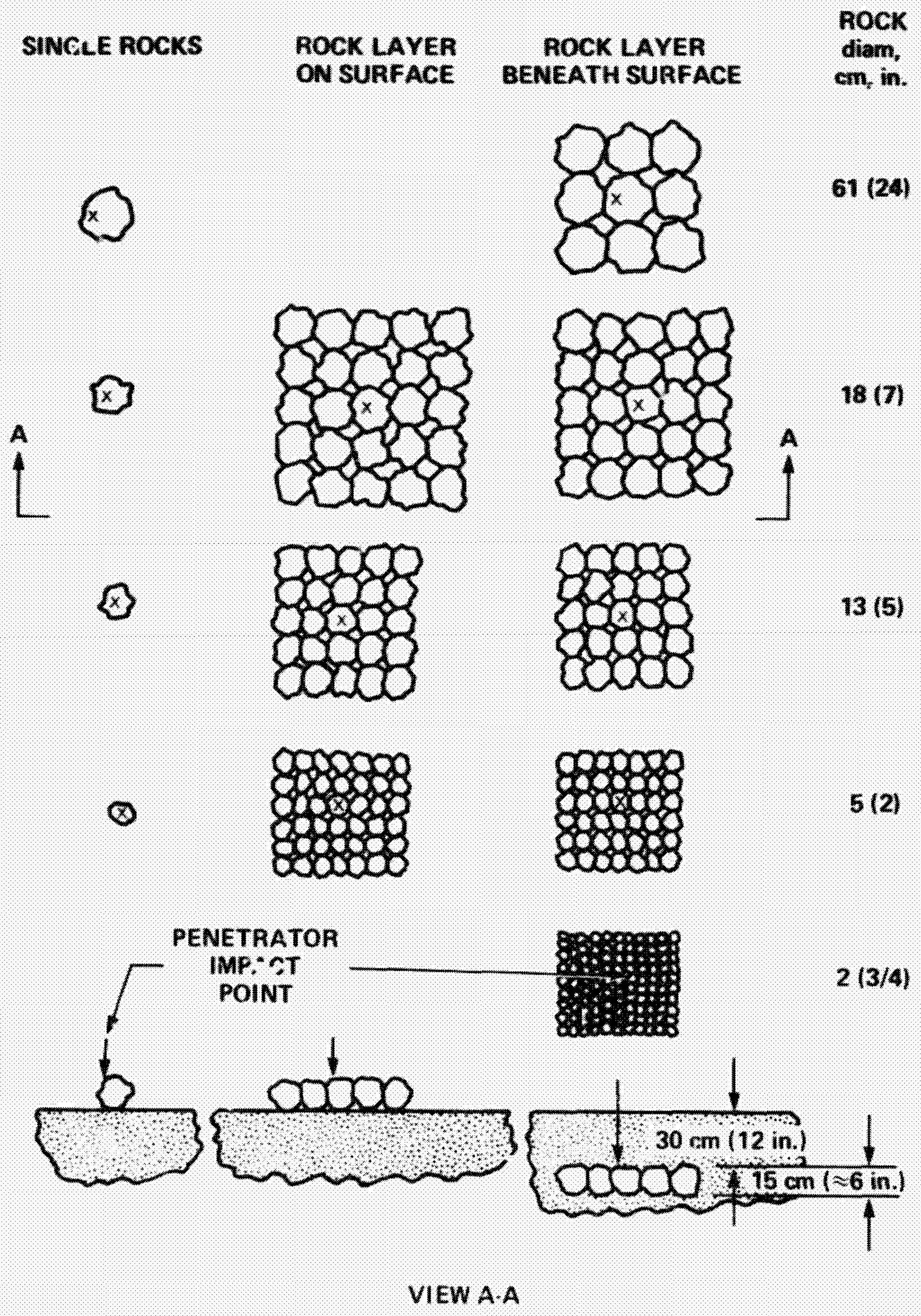
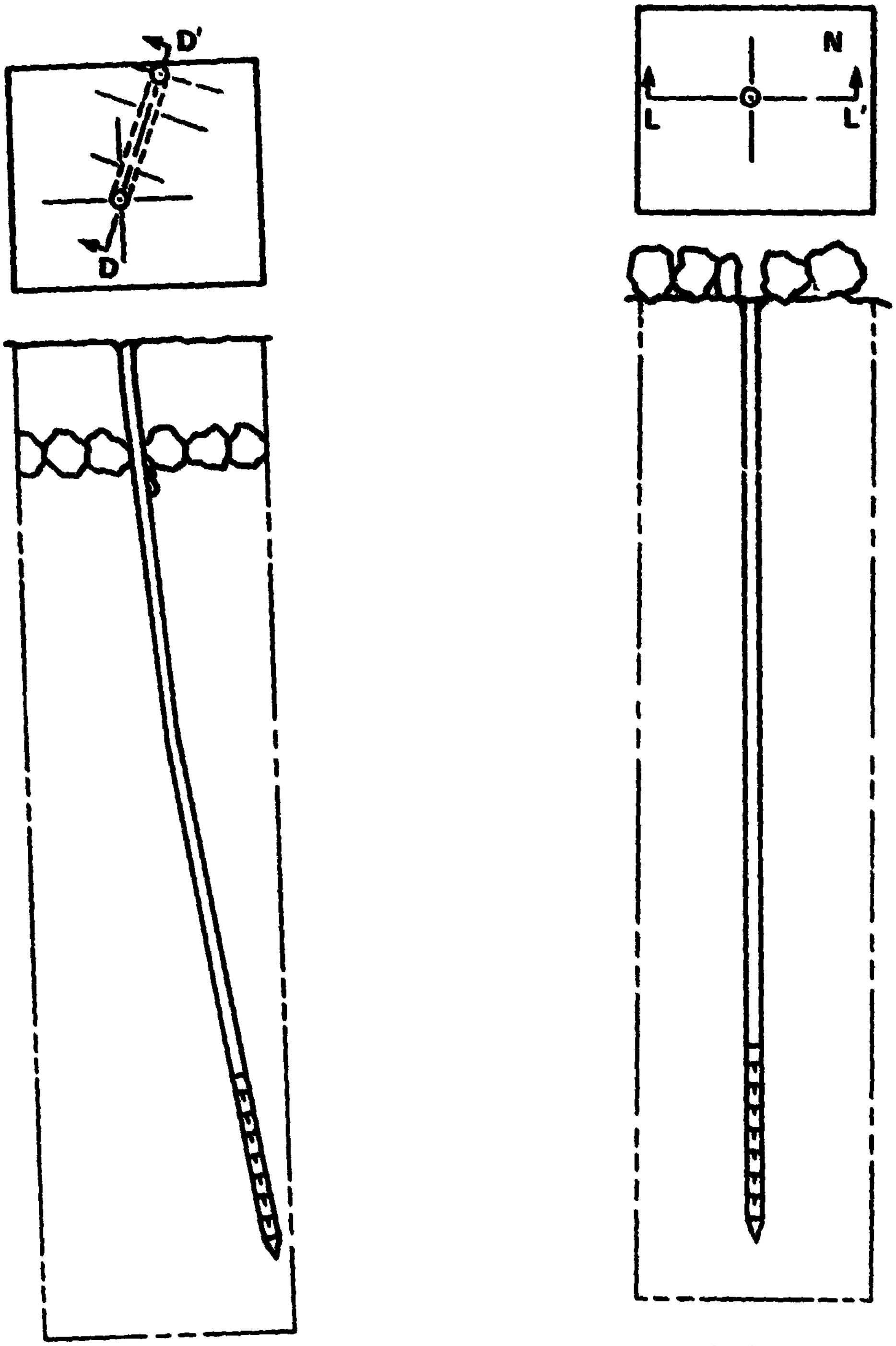


Figure 8.- Layout of test site. The penetrator impact points are located at one-half the radius of the rock.

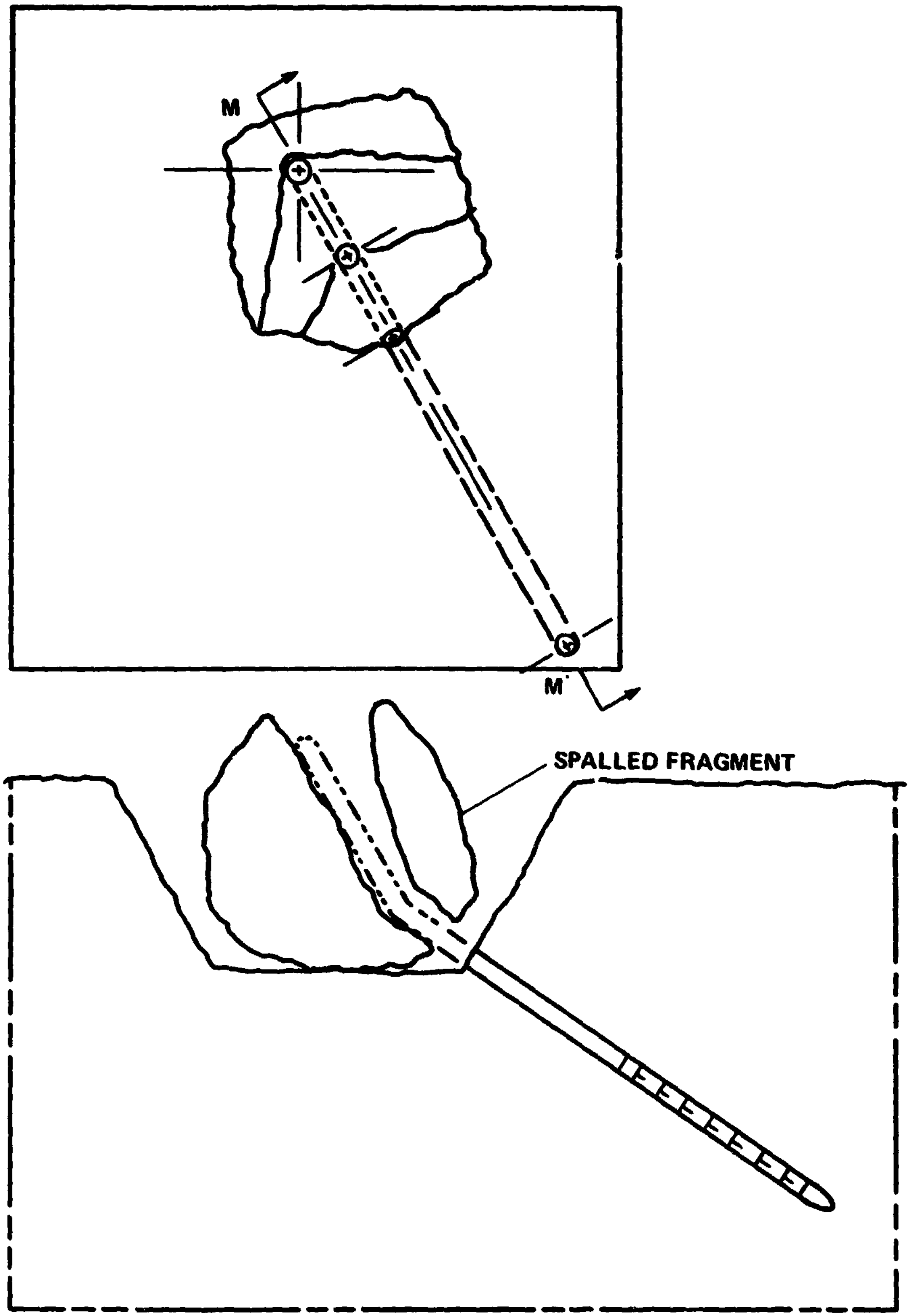
Figure 9.- One side of the hole was removed to expose a complete cross section of the hole made by the penetrator.



CROSS SECTION
D-D'

CROSS SECTION
L-L'

Figure 10.- Cross sections of the hole after each penetrator test.



CROSS SECTION
M-M'

Figure 10.- Concluded.

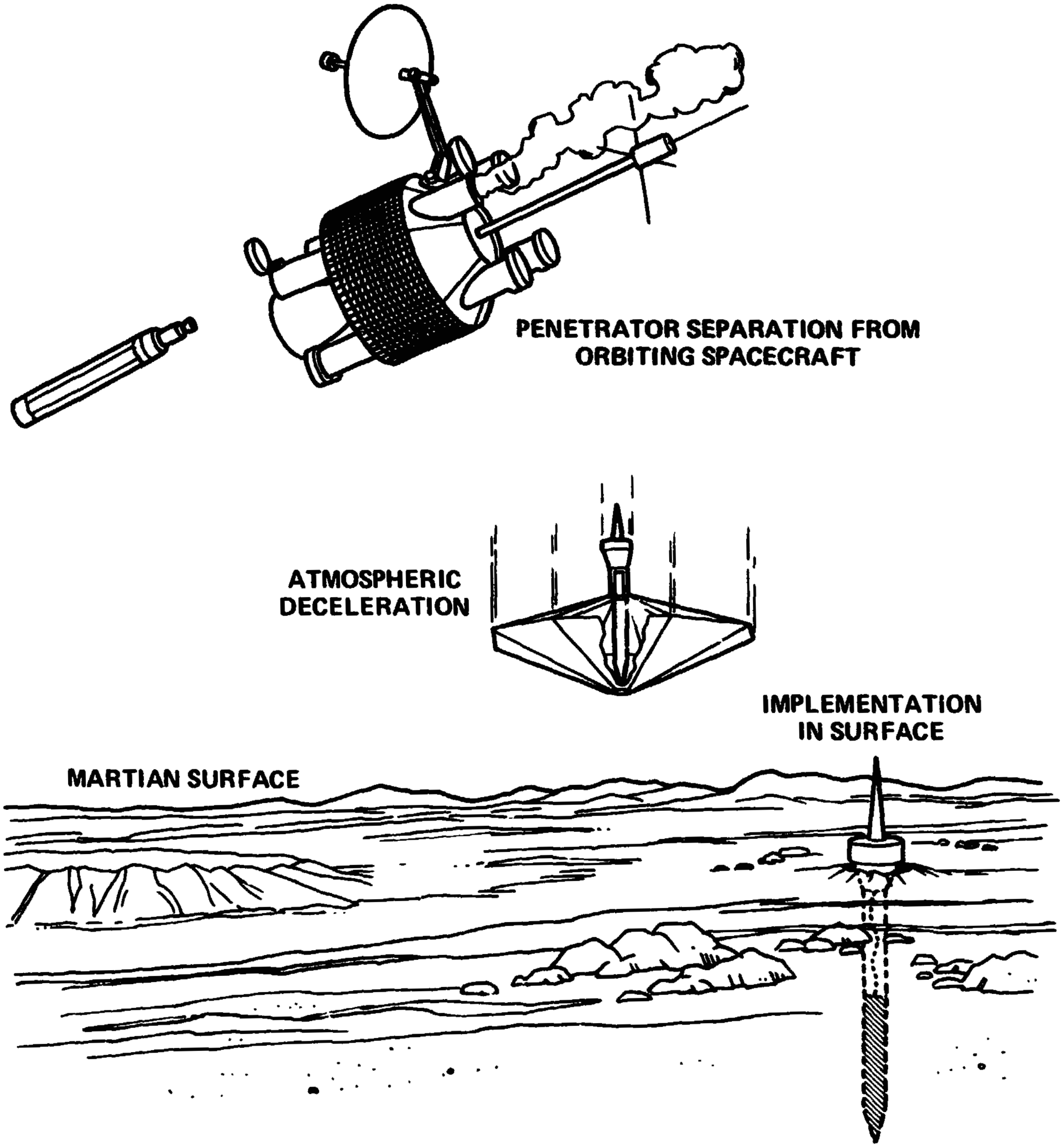


Figure 11.- Penetrator deployment on Mars.

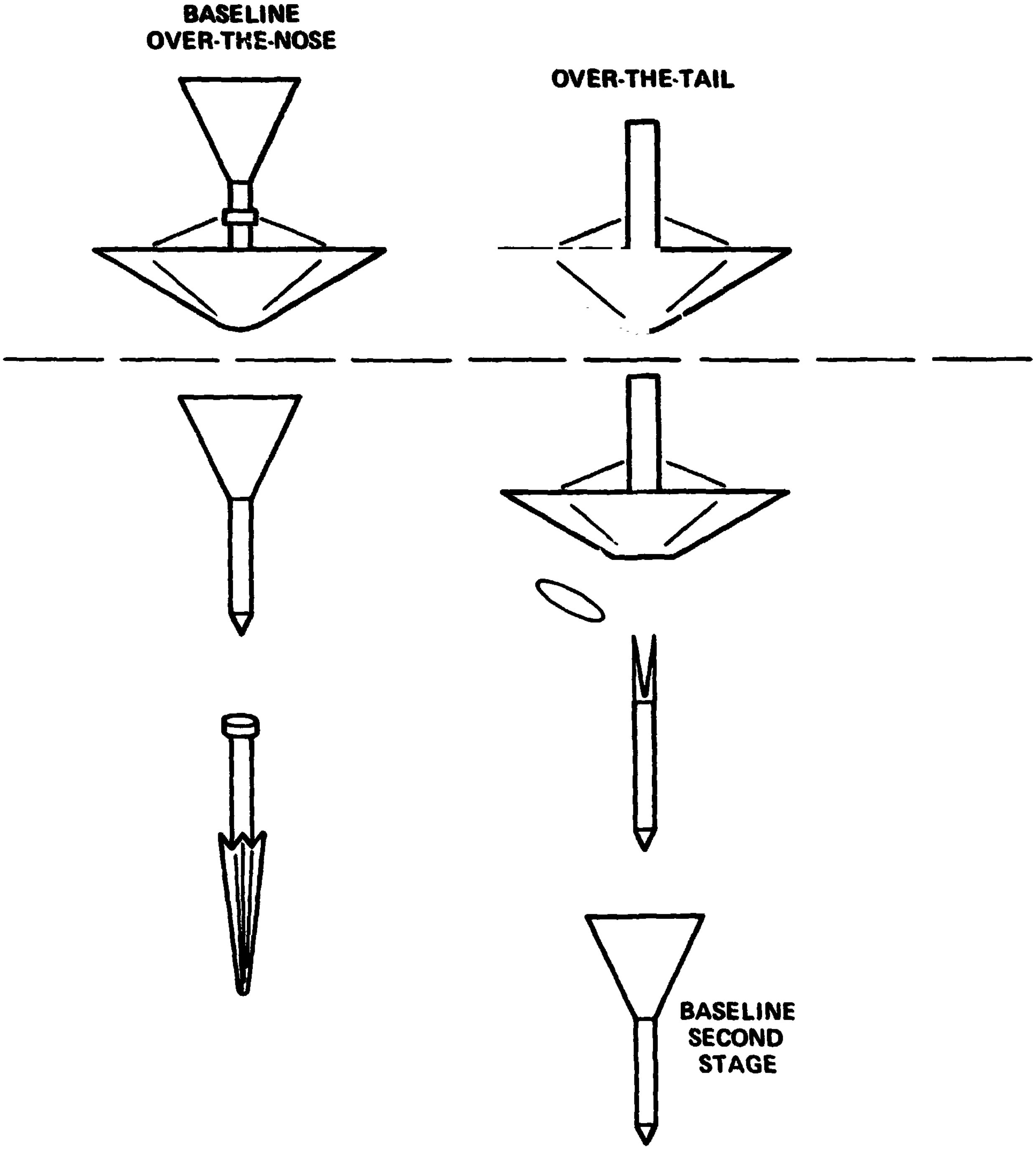


Figure 12.- Jettisoning concepts.

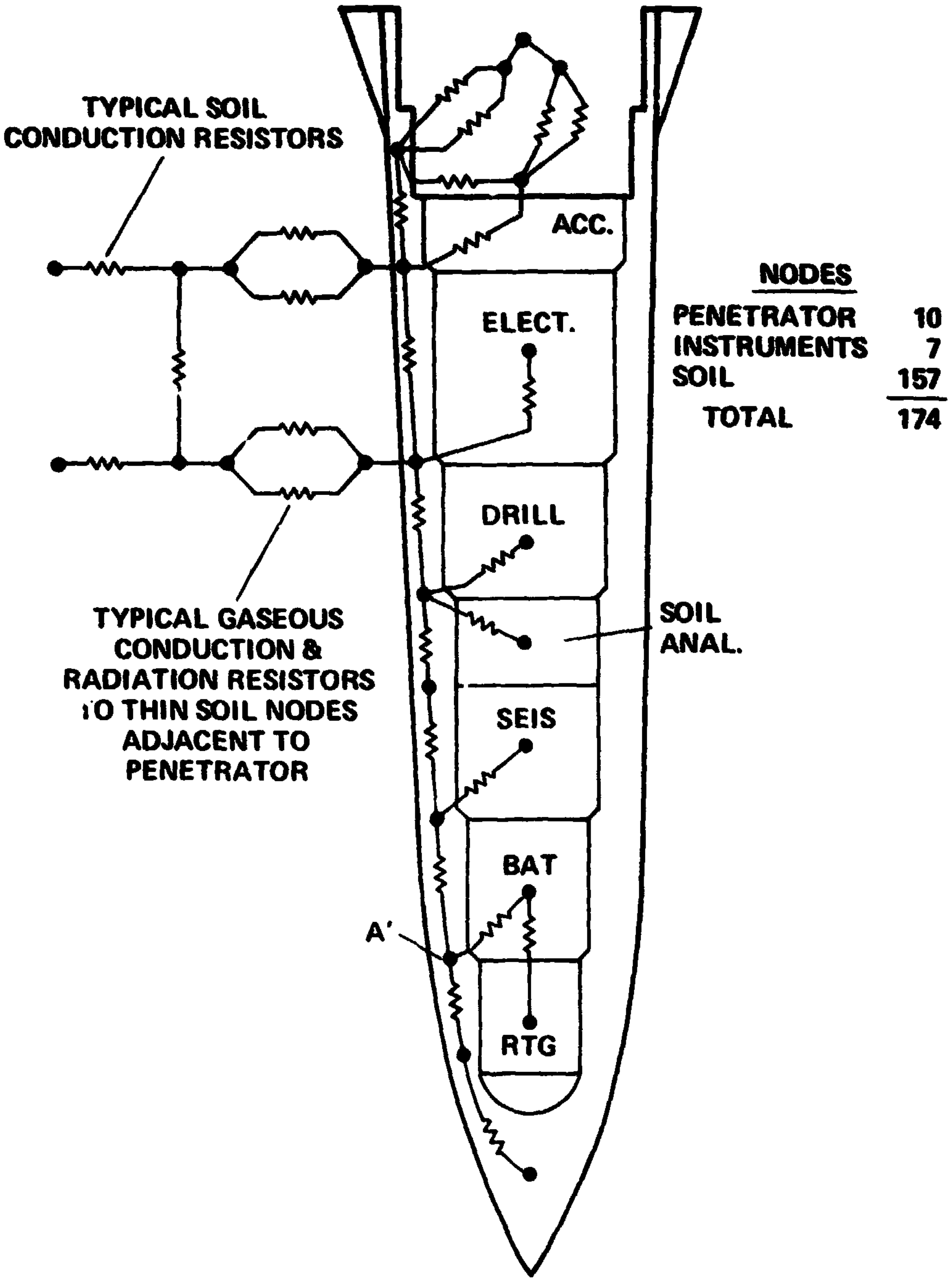


Figure 13.- Penetrator forebody thermal model.

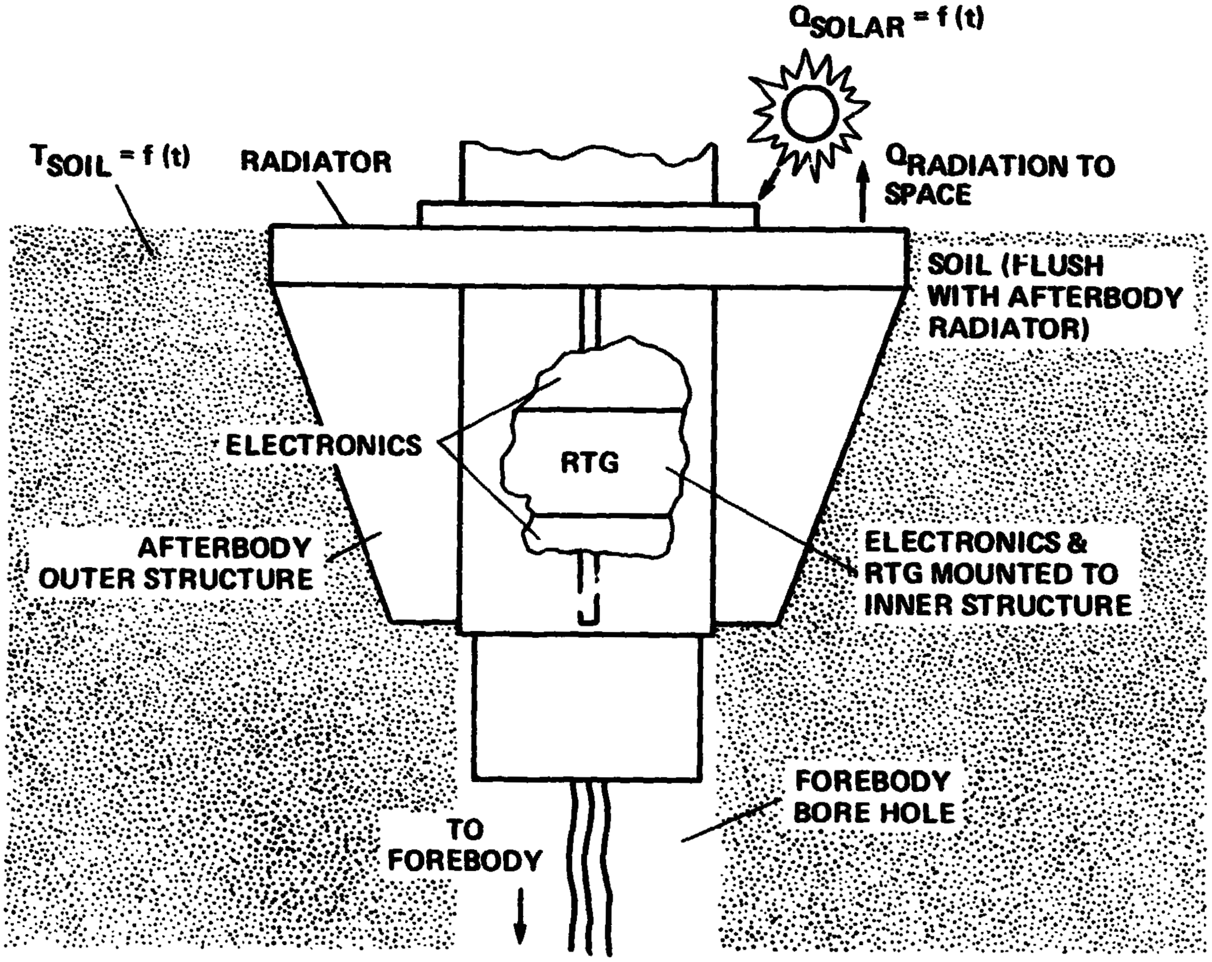
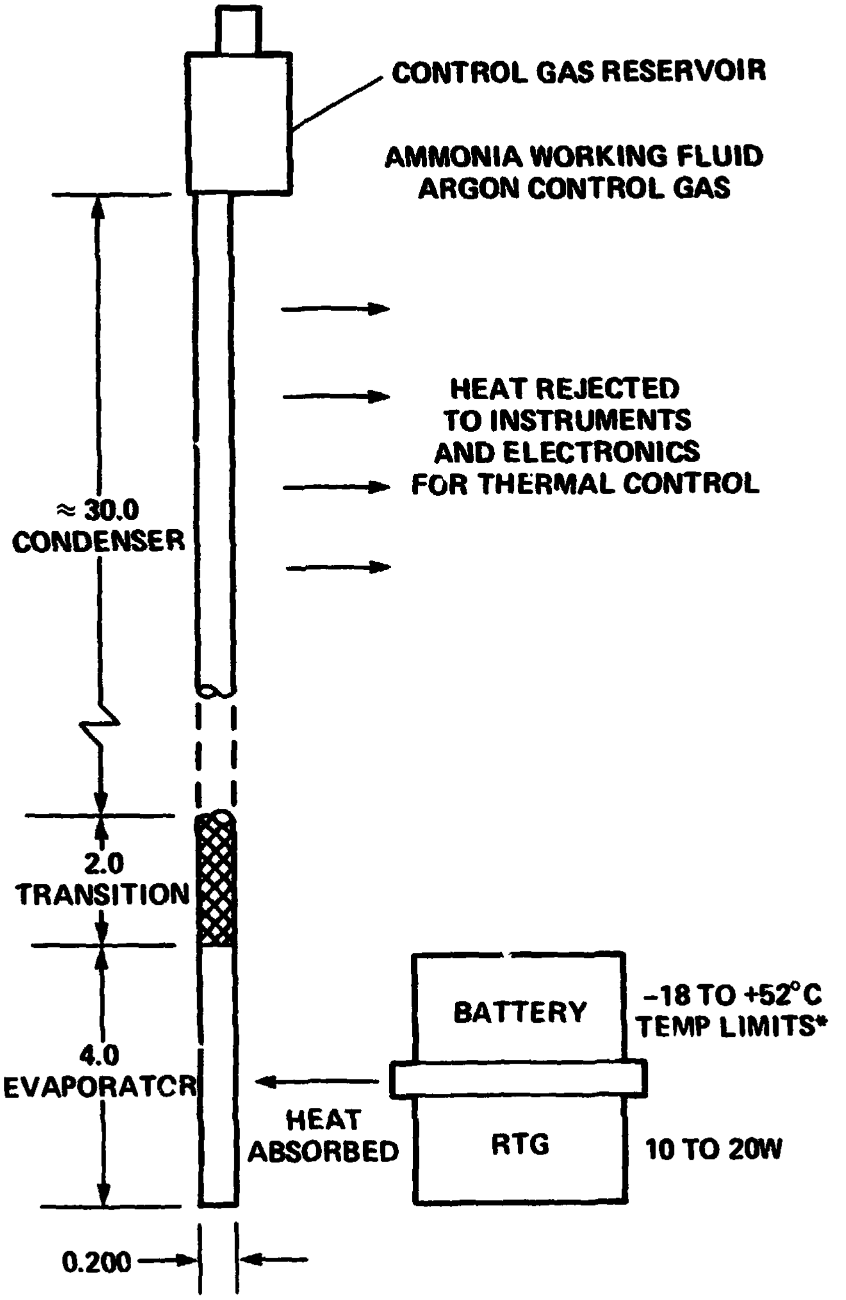


Figure 14.- Penetrator afterbody deployment.



*HEAT PIPE STARTS CONDUCTION AT EVAPORATOR TEMP OF -18°C. HEAT PIPE FULLY CONDUCTING AT EVAPORATOR TEMP OF 10°C.

Figure 15.- Penetrator forebody heat pipe concept.

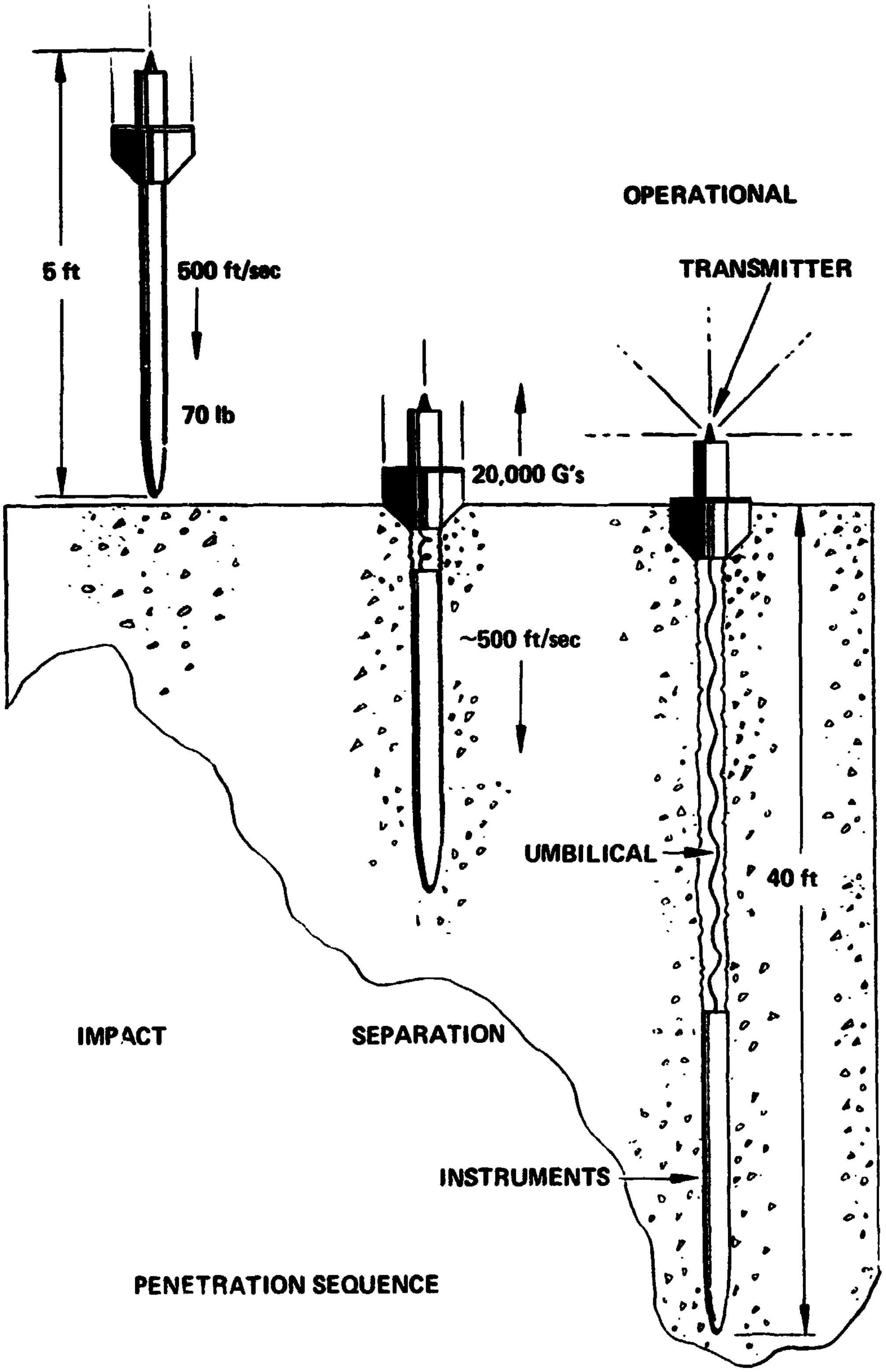
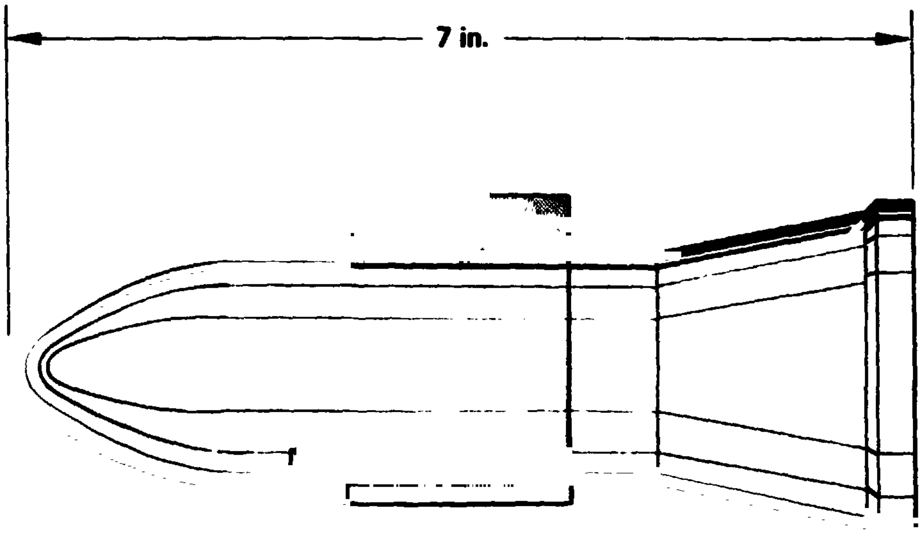
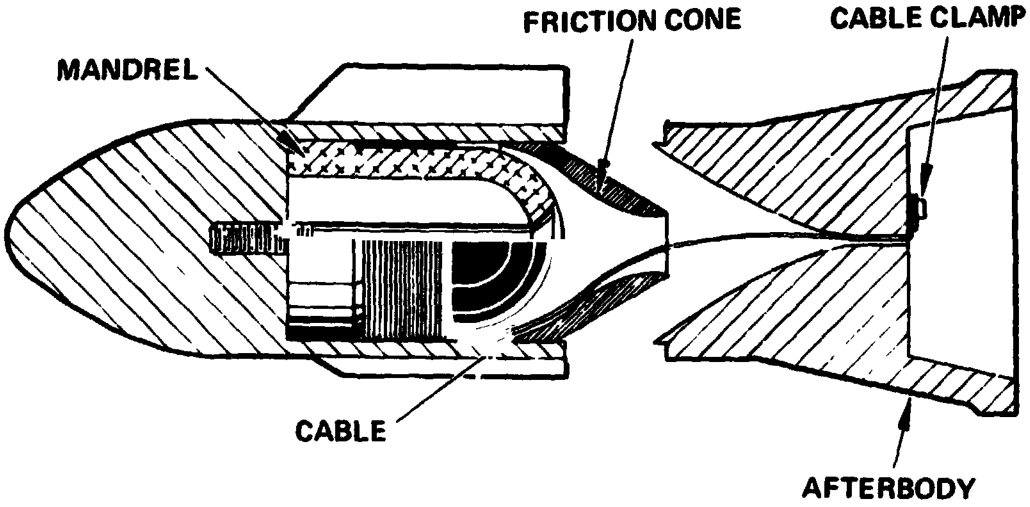

OPERATIONAL
TRANSMITTER
5 ft
500 ft/sec
70 lb
20,000 G's
~500 ft/sec
UMBILICAL
40 ft
IMPACT
SEPARATION
INSTRUMENTS
PENETRATION SEQUENCE

Figure 16



ASSEMBLED MODEL



UMBILICAL TEST MODEL

Figure 17.- 1/2-scale test model.

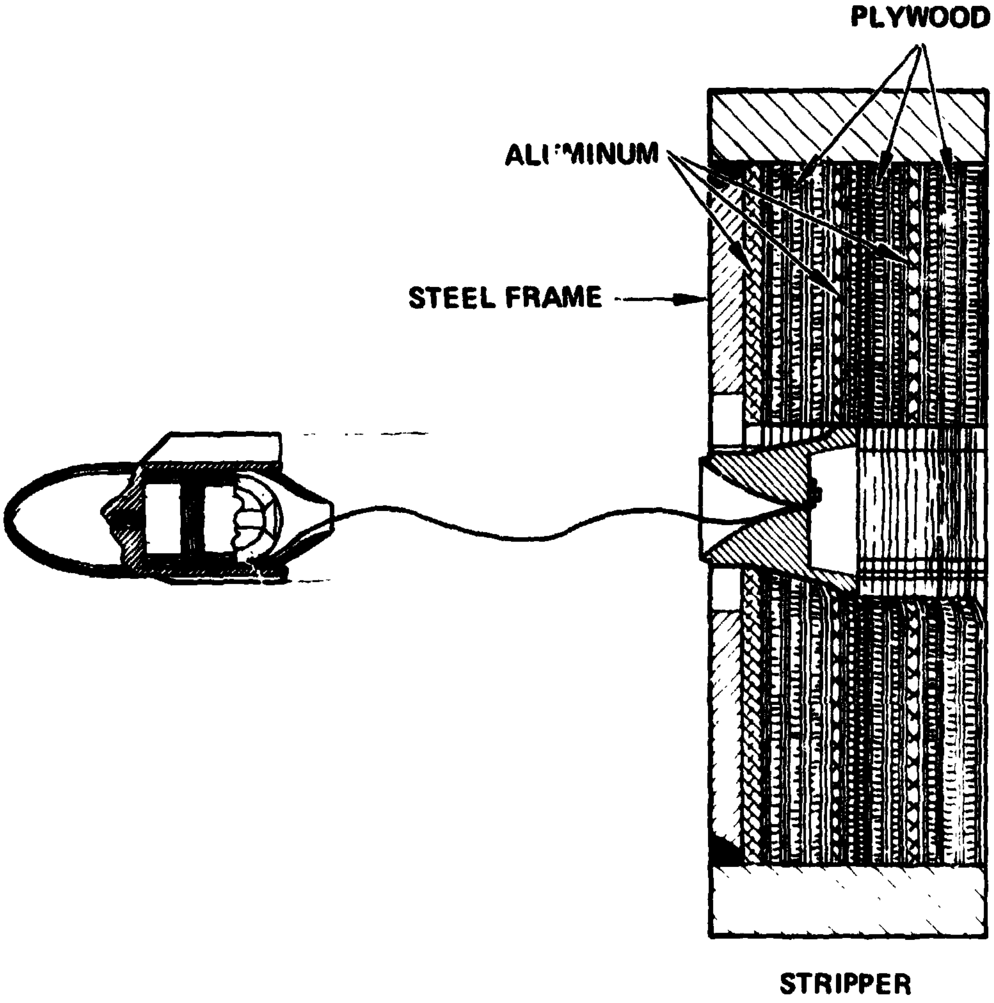


Figure 18.- Cable deployment test rig.

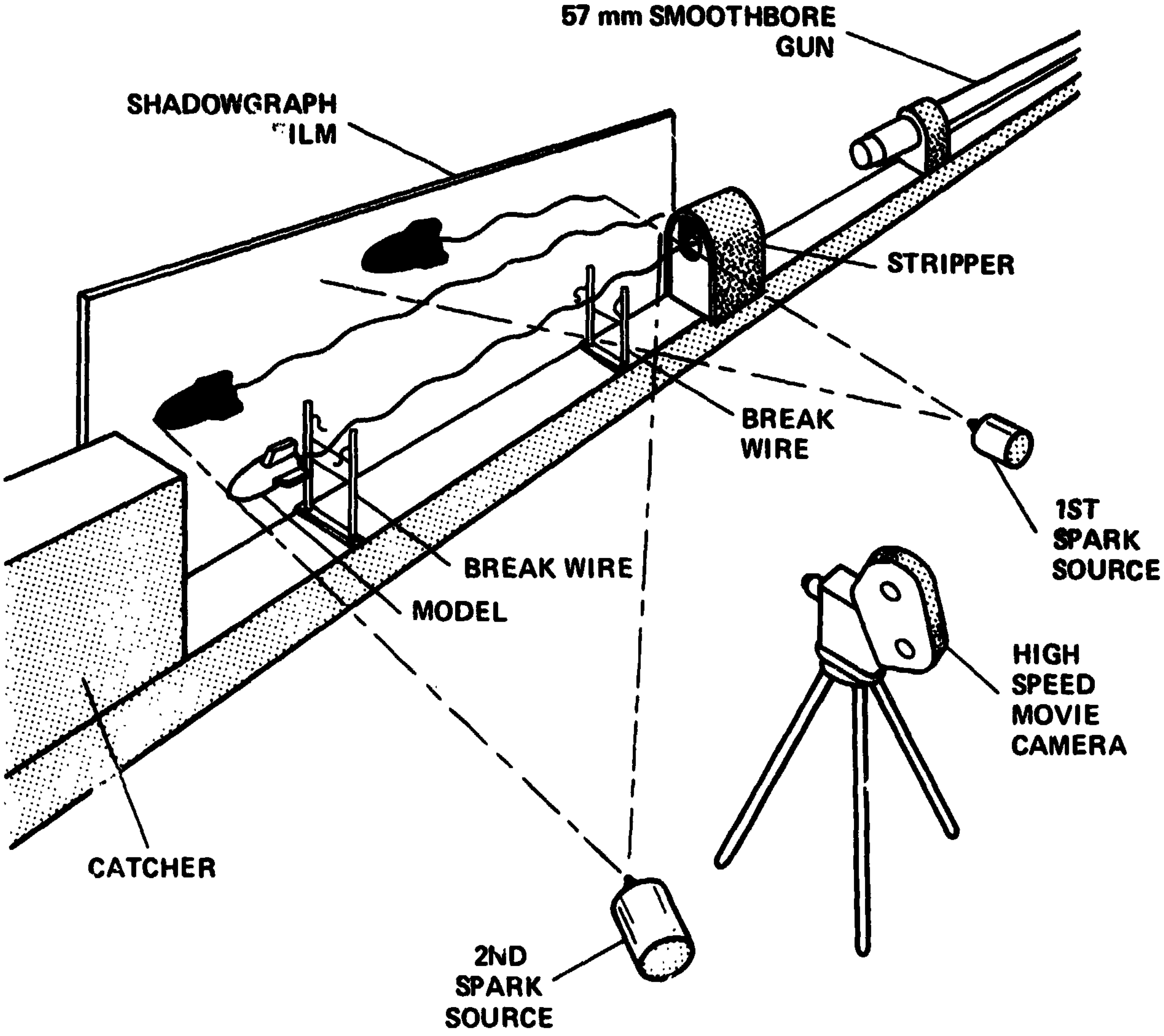


Figure 19.- Cable deployment photo instrumentation.