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EXPERIMENTS ON ASTEROIDS USING HARD LANDERS

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The possibility and desirability of science on hard lander missions to asteroids are examined using the Westphal Penetrator Study as a basis. Imagery and chemical information appear to be the most significant science to be obtained. The latter, particularly a detailed chemical analysis performed on an uncontaminated sample, 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.

INTRODUCTION

A few philosophical comments are perhaps pertinent relative to the general subject of this workshop: the study of asteroids. There is a frame of thinking about all uninvestigated objects of the solar system that relates them to the meteorites that we have available for intensive study in our laboratories. This is certainly a practical zero order framework--meteorites do represent a rather diverse set of objects, and, as previous papers have shown, optical observations provide correlations that allow classification of asteroids into types that might correspond to the meteorites we have in the laboratory.

On the other hand, it may be recalled that none of the three solar system objects that we have investigated intensively--the Earth, Moon, and Mars--have turned out to be simply related to any meteorite class. This, in spite of speculations about the Moon and Mars, previous to their intensive investigations, that tended to follow the same pathways as the present discussions about asteroids.

Thus, without minimizing the meteorite framework of thinking about asteroids, let us keep our minds open for the types of surprises that were uncovered in the investigations of the Moon and Mars.

Similarly, a more detailed framework of thinking about the solar system is built about the idea of volatility, or inversely, condensation. Whether or not this turns out to be fundamental, it is useful in focusing attention on the concentrations of a few key elements. At the same time, here too, we should not restrict ourselves at this stage to analyzing just for these magic key elements, or we run the danger of missing the important new knowledge that the study of new objects may provide.

A second general point, with specific relevance to the topic of this paper, is the role of hard landers in the study of an extraterrestrial object. A general classification of investigations of such objects might be ordered as in Table 1.

Table 1. Classification of Extraterrestrial Object Investigations

1. Earth-based Studies
2. Studies from Near-Earth Orbit
3. Flybys
4. Object Orbiters
5. Hard Landers
6. Soft Landers
7. Sample Return

In this list, there is some experience relative to each of these modes of exploration except for Number 5. Thus, the topic of this paper has less concrete data to support it than many others in this workshop. The authors have knowledge of only one intensive study of the possibility of doing science on hard landers, namely the *Final Report and Recommendations of the Ad Hoc Surface Penetration Science Committee* (Westphal, 1976), which was directed mainly towards Mars exploration.

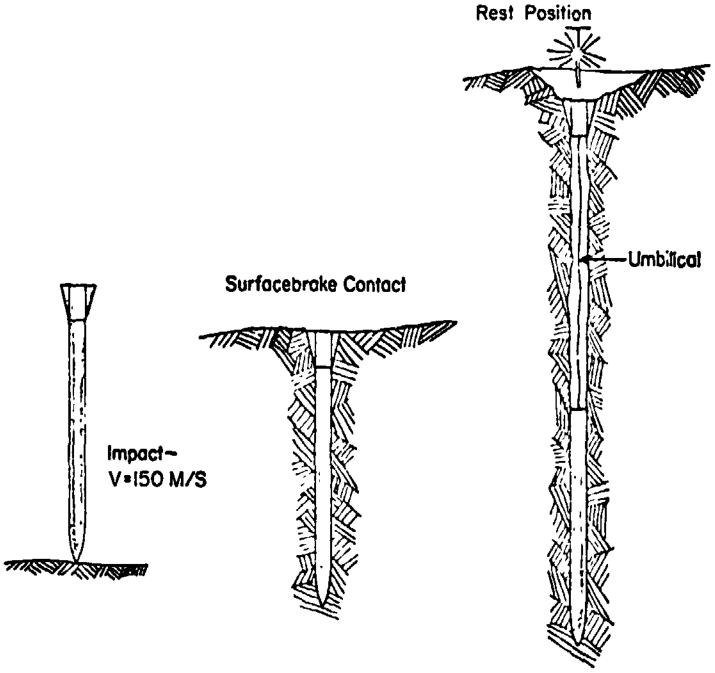

Fig. 1. Sequence for penetrator emplantation.

In addition, there have been less extensive studies of other hard lander types of missions; we will base our remarks on the possibilities of science using penetrators--objects that are dropped from an orbiting or flyby type of vehicle, which have sufficient braking power to reduce their impact velocity to about 0.1-0.2 km/sec. The penetrators typically will consist of two parts--a forebody which is a torpedo-type object which penetrates and comes to rest 1-10 m below the surface and which contains most of the science payload, and an afterbody which remains on the surface, provides communication with the mother vehicle (or Earth), and has minimal science (Manning, 1977) (see Figure 1).

The figure shows a schematic mission sequence considered by the Westphal Committee for a Mars Penetrator. Table 2 (again from the Westphal report) shows nominal Mars Penetrator characteristics. Note the small science payload--7 kg--that presumably will always be characteristic of such hard landers.

Table 2. Nominal Mars Penetrator Characteristics[a]

Complete Penetrator	
Weight	31 kg
Principal Diameter	9 cm
Frontal Area	64 cm^2
Sectional Density	0.5 kg/cm^2
Length	140 cm
Payload[b]	
Weight	7 kg
Volume	4500 cm^3
Power Output (RTG)	0.3 watt
Battery Supplement	1.0 watt hr/day
Data Storage	2 × 10^5 bits
Forebody Probe	
Weight	28 kg
Principal Diameter	9 cm
Frontal Area	64 cm^2
Sectional Density	0.5 kg/cm^2
Length	123 cm
Detachable Afterbody	
Weight	3 kg
Principal Diameter	23 cm
Frontal Area	350 cm^2
Sectional Density	0.01 kg/cm^2
Length	28 cm

[a] From Final Report and Recommendations of the Ad Hoc Surface Penetrator Science Committee (J.A. Westphal, Chairman, August 1976).

[b] Includes science and supporting electronics.

Obviously, for asteroid missions, some of the characteristics designed for a martian mission would have to be modified (a very obvious example is a replacement for the parachute braking in the case of an atmosphereless asteroid body). The figure and tables are given to provide some general framework for talking about hard landing missions to asteroids. It will be assumed that the type of science that was considered by the Westphal Committee for a Penetration Mission to Mars is representative of the type of science that could be done on a hard landing mission to an asteroid.

One more comment about penetrators as a specific type of hard lander; one of their characteristics is that they examine material that is some distance (1-10 m) below the surface. This has special science implications and is in contrast to the type of information obtained by optical and x-ray techniques, either from Earth or on flyby or orbital missions. The topmost surface of an extraterrestrial object *may* be modified so as to be significantly different from that of the material deeper down. This modification may be due to interaction with the atmosphere or with interplanetary radiations or particles, and may produce both physical and chemical effects. An example is the permafrost expected by many to be present below the surface of Mars, whereas the surface examined by Viking was very dry. Penetrators are especially suited for detecting such effects.

A final general comment might be made about the appropriateness of hard landers in the study of asteroids. An important characteristic that has been established about asteroids is that there are several significantly different types, as judged by the observational techniques available so far (McCord, 1978; Morrison, 1978). Thus, asteroid missions in the foreseeable future are typically thought of as involving investigation of several asteroids--three, four, or more--on the same mission. Since such a mission may very well involve a flyby or relatively short-term encounter with each asteroid, there is a premium on the type of science that can be performed on several asteroids. The emplantation of one or more penetrators on each asteroid as the mother vehicle passes by is an attractive feature of a mission carrying penetrators. It could provide much more information than could be obtained by remote sensing; also, it would not have the weight requirements of landing a Surveyor or Viking type spacecraft on each asteroid.

Before going into the science possibilities, the authors must make the obvious cautionary statement: the only practical and engineering aspects that have been considered are the assumptions that the Westphal Penetrator study--directed toward Mars--represents a zero-th order approximation for the capability of a hard landing science mission to asteroids.

POSSIBLE HARD LANDER SCIENCE

In considering the possible scientific results that might be achieved on a penetrator on an asteroid, this paper starts from the results of the Westphal Committee. Table 3 lists (with a little adaptation) the types of measurements that are considered practical on such a mission.

Table 3. Possible Asteroid Hard Lander Science (after Westphal, 1976)

Probe Forebody	Detachable Afterbody
Seismicity	Imagery
Chemical Composition	Near-Space Environment
Hydrogen/Water Measurements	Magnetic Properties
Heat Flow	

The Westphal Committee considered it practical to have some imaging capabilities on the afterbody, even though the acceleration experienced would be appreciably greater than on the penetrator forebody itself. The height from which pictures could be obtained would be small, but the scientific information would be significant. It would bear not only on the processes occurring on the asteroid surface (*e.g.*, cratering, presence or absence of a regolith) but also could affect the interpretation of remote sensing measurements such as radar reflectivity.

Measurements could also be made in the afterbody on the near-space environment of the asteroid. For example, the steady-state presence of gases and ions could provide information on the degassing of the object even if no, or minimal, mass analyses were involved. Similarly, the presence of magnetic material on the surface of the asteroid could be established (to the level performed by Surveyor or Viking) using primitive imaging capabilities.

The deceleration profile on the forebody probe of a penetrator as it came to rest in the subsurface material should be a very sensitive distinguishing indicator between the different classes of meteorites that are proposed as models for asteroids (pallasites, ordinary chondrites and carbonaceous chondrites). In fact, planning for the complete range of mechanical properties represented by such models may represent a significant constraint on a mission planning to go to different asteroids.

The emplantation of a seismometer by penetrators has, in the past, been a prime reason for advocating such missions to terrestrial type bodies. The usefulness of seismometers on asteroids is not so obvious. The very low seismicity of the Moon, and the paucity (if any) of results from Viking on Mars, make dim the prospects for signals from an instrument on an asteroid. Before dismissing such measurements completely, however, more complete analysis should be made of the possibility that seismic signals on an asteroid would be enhanced due to, for example, an increased frequency of impacts by nearby massive objects. Also, the engineering possibilities of obtaining significant seismic information by setting off explosive charges on an asteroid after seismometer emplantation should be examined (Wood, personal communication, 1978).

Perhaps the most significant scientific result that could come from a penetrator-type mission to an asteroid would be the more complete chemical characterization than can be deduced from either Earth-based, Earth-orbit or flyby observations. As indicated in the introduction, such remote observations provide the first gross classification of an object from information either about the most abundant minerals or about some specific chemical elements that are identified (Haines *et al.*, 1976). The experience on the Moon and Mars has shown that a complete chemical analysis provides surprises and details not obtainable by such remote sensing devices. Of course, the ultimate technique--sample return--can be expected to be even more productive, especially as regards chronological and other isotopic information.

Because of the potential of this chemical approach, it is worth focusing on some practical details as well as on some detailed results that might be expected.

Table 4 summarizes the techniques that have been considered for a penetrator-type mission for studying the chemical composition and chemical state of the material around an emplaced penetrator. In all four cases, there is some evidence that the hardware involved can survive the decelerations involved in emplantation. The first two techniques measure the bulk properties of the material surrounding the penetrator. The last two require the acquisition of a sample. Because the emplantation process modifies somewhat both the physical and chemical state of the material just outside the penetrator, a drill, or other means of obtaining an unaltered sample, is needed. Some work has been done indicating that such a sample acquisition system is practical. In the case of hard landers other than penetrators, this uncontaminated sample acquisition may be even simpler to accomplish.

The *in situ* gamma-ray measurements, if possible, are among the simplest that might be performed on a penetrator (Metzger and Parker, 1976). The presence of a nearby RTG source of neutrons and gamma-rays can be either a hazard or a benefit. In the cleanest experiment of this type, data would be obtained on the potassium and radioactive heavy element concentrations of the nearby material. The results should allow a discrimination at least between the pallasite and chondrite models of the asteroids. More generally,

Table 4. Possible Techniques for Studying Chemical State and Composition on Penetrator Missions to Asteroids

1. *In situ* Gamma-Ray Measurements
    a. "Natural" Radioactivity of Surroundings (K, Th, U)
    b. Nuclear Processes Induced by Cosmic-Rays or RTG Neutrons (*e.g.*, O, Si, Fe, H)
2. Thermal Neutron Measurements
    (Sensitive to H)
3. Chemical Analyses of Procured Sample
    (All principal chemical elements except H; selected minor and trace elements.)
4. Analyses of State of Water in Procured Sample
    ("Free-water," absorbed water, water of hydration, chemically bound water)

they would provide data on the concentration of a relatively volatile element, potassium, and of the refractory elements, uranium and thorium. In addition, the data would bear on the radioactive heat production in the asteroid.

If the gamma-ray measurement could be extended to include, *e.g.*, Si, Fe and H (making use of the neutrons from the RTGs or cosmic-rays), the discrimination between candidate meteorite classes would be complete. Again, in somewhat more basic terms, the characterization of the asteroid in terms of its position in a condensation type scenario of the formation of the solar system bodies would be clarified.

Another measurement that could provide data on the bulk properties of the matter surrounding the emplanted penetrator is that of the thermal neutrons present. The RTG power sources currently considered for penetrators produce some 10^5 neutrons per second. This is the range of intensity that has been used in terrestrial applications of hydrogen determination by neutron moderation techniques (*e.g.*, Long and French, 1967). It is expected that this technique could determine hydrogen with a sensitivity of 0.05% by weight (water content down to 0.5% by weight) although, of course, it would not distinguish between hydrogen in the form of water and that in the form of carbon compounds. Both forms would be indications of carbonaceous chondrite material, or more basically, of the presence of very volatile constituents in the body. In terms of possible eventual uses of asteroids for self-sufficient extraterrestrial activities, the availability of hydrogen is an extremely important resource.

More complete chemical characterization of a sample on a hard lander mission depends on the acquisition of an uncontaminated sample. As mentioned above, this does not appear to be an impossible objective, particularly for a body that is not appreciably harder than a basaltic rock. Miniature hardened instruments appear to be available to perform rather complete chemical analyses of such a sample. A currently considered instrument would use an alpha particle technique for the light chemical elements and x-ray detection for the heavier elements.

Table 5. Chemical Analyses on Hard Lander Missions to Asteroids

(Expected accuracies (at 90% confidence limit) in weight percent for principal chemical elements[a])

Element	α + p + x-ray Modes
C	± 0.2
O	± 0.7
Na	± 0.2
Mg	± 0.8
Al	± 0.4
Si	± 1.2
K	± 0.2
Ca	± 0.2
Ti	± 0.15
Fe	± 0.4

[a]From Economou and Turkevich, 1976.

Table 5 gives the presently considered achievable accuracies of such analyses for the principal chemical elements (Economou and Turkevich, 1976). The accuracies are such that (especially if a separate hydrogen determination is made), more than 99% of atoms in the sample will be identified and determined, a reasonable normative mineral composition can be deduced, as well as the state of oxidation of the system.

Thus, the material examined would be characterized considerably beyond the meteorite classification and even beyond that achieved on the Surveyor missions to the Moon, certainly beyond that achieved on Viking. The establishment of the major constituents would permit more soundly based interpretations of the abundances of the minor and trace elements.

Table 6 gives examples of the sensitivity considered achievable by present day instruments for minor elements (Economou and Turkevich, 1976). These sensitivities depend somewhat on the state-of-the-art of semiconductor x-ray detectors which is continually improving. Better sensitivities may well be achieved by the time an actual asteroid mission is undertaken. Even the present sensitivities provide examples of chemical elements (*e.g.*, C, K, Ti, Zr), whose abundances are used to characterize condensation conditions at the time of formation of solar system bodies.

In conclusion, it is likely that remote sensing measurements will not answer definitively very important questions about the nature of asteroids, their history and relationship to other bodies of the solar system. *In situ* chemical analyses are probably required to establish conclusively the relationships of asteroids to the meteorites with which they are frequently compared. Such analyses will also be needed to place asteroids in the condensation scenario often invoked for the history of the solar system. It is by such more complete chemical analyses that the spectral characteristics of the Moon and Mars have been established and it should therefore be a good bet that asteroids will likewise provide new and intriguing data.

Even such *in situ* measurements, however, are not likely to provide the isotopic data needed to establish the chronology of asteroid formation and of their exposure to the space environment. Nor will it be possible to place them in the hierarchy of oxygen isotope anomaly systematics that is emerging for solar system bodies. For such data, returned samples appear to be required.

Table 6. Chemical Analyses on Hard Lander Missions to Asteroids--Examples of Expected $\alpha + p +$ x-ray Sensitivities for Minor Elements, Evaluated for a Basalt Matrix Using Alpha and Auxiliary Sources[a]

Element	Sensitivity (Weight %)	Element	Sensitivity (Weight %)
H[b]	0.03	Rb	0.001
N	0.2	Sr	0.001
F	0.05	Y	0.0005
P	0.2	Zr	0.0005
S	0.1	Ba	0.001
Cl	0.1	La	0.001
K[c]	0.07	Ce	0.0008
V	0.03	Nd	0.0008
Cr	0.02	Sm	0.0005
Mn	0.03	Pb	0.005
Ni	0.02	Th	0.005
Cu	0.02	U	0.005
Zn	0.02		

[a] From Economou and Turkevich, 1976.

[b] Using thermal neutron detection techniques.

[c] Sensitivity for K expected in the presence of a few weight % of Ca.

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DISCUSSION

ARNOLD: A comment on the list of penetrator instruments. This paper reinforces my impression that the combined alpha instrument is best for penetrator use. There is a potential instrument being developed by Trombka using a pulsed neutron source which I think can make the gamma-ray experiment more attractive than the simple gamma-ray experiment described here. The biggest disadvantage of this gamma-ray experiment is that you can't use a germanium crystal because temperatures are too high (about 150°K).

ANDERS: It seems to me the gamma-ray and alpha-ray instruments are complementary. Gamma-ray spectrometry from orbit does a superb job for uranium, thorium and potassium and gets regional averages. Then the alpha instrument in turn goes below the regolith, and also does considerably better on elements such as calcium.

ARNOLD: I agree if you put the germanium in orbit and the alpha spectrometer down below you would indeed have the best of both worlds. We were really discussing the tradeoff in the penetrator. I think it would be fantastic if you could put both instruments in the penetrator.

NIEHOFF: How about an x-ray diffractometer? There was a Viking proposal for a small device of this type. If mineralogy is that much more important than elemental abundances, then some instrument of this type should be looked at.

FANALE: Mineralogy is in many ways more important because you can take the same mass balance and put it, as nature has, in a thousand different crucibles and produce a variety of mineralogies. We might be better off spending our money doing a mineralogical experiment that is designed to look at the bland materials you find in carbonaceous chondrites and which give no x-ray lines on a laboratory diffractometer. So I think you ought to think seriously about that.

ECONOMOU: There are at least two groups working on diffractometers. Detectors are a problem; they must have good resolution and must survive penetrator emplacement.

ANDERS: Under ideal conditions in the laboratory a diffractometer can identify adequately the two or three most abundant minerals in typical mixtures such as are found in nature. It cannot cope well with the less abundant minerals in such a mixture unless they are first enriched by a separation. It probably cannot cope well with regolith-type material, containing glasses, amorphous materials, and clay minerals that do not give diffraction patterns. I think it would be a complete waste of effort to send such an instrument to an asteroid.

McCORD: Is there a problem getting enough velocity to emplace the penetrator?

NIEHOFF: No, it turns out the same tube from which a penetrator was launched at Mars to make it deorbit provides enough energy for you to get an impact on an asteroid. So it is a fortuitous complementary design. The one system difference is the need for a device to maintain the attitude from the time of launch until impact and that weighs on the order of 10 kg.

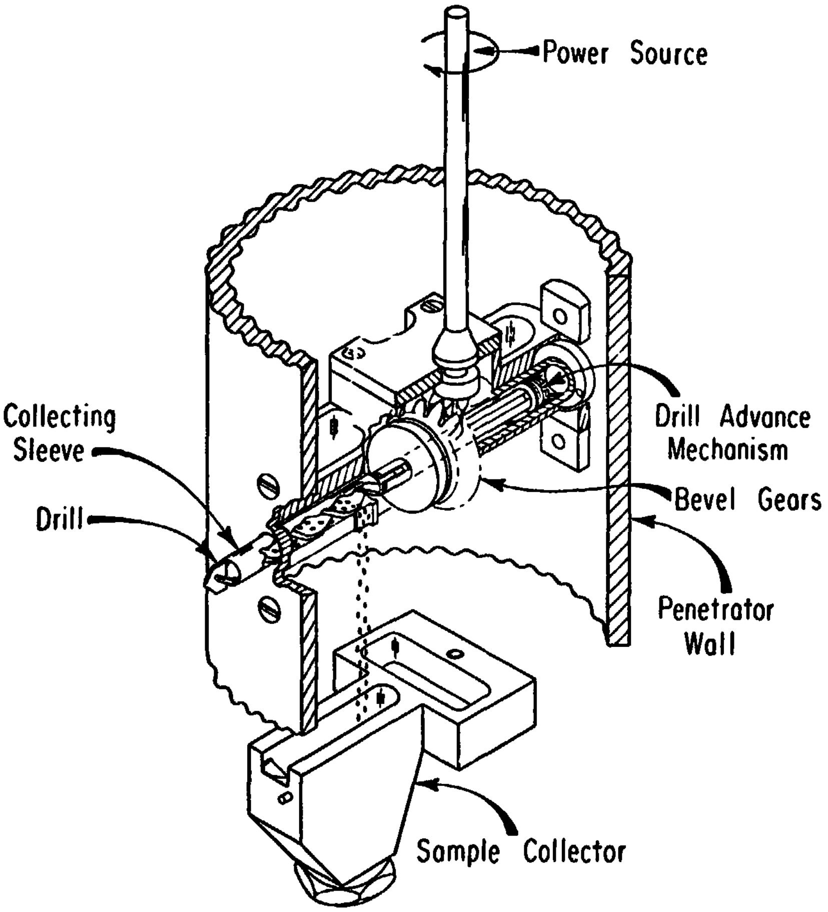
McCORD: If a penetrator impacts one of these unconsolidated objects, will it go too deep and rip the umbilical cord?

NIEHOFF: Yes, it could. There are design alternatives which could alleviate this problem.

SHOEMAKER: How does the alpha scattering instrument look at the soil or rock?

ECONOMOU: The material adjacent to the penetrator is modified by the impact, so to get a sample we must penetrate this boundary layer which is a few millimeters thick. We have a working prototype of a device that goes into the soil and brings a sample back to our instruments. (See figure below from a report by Turkevich, A. L., Economou, T. E., and Franzgrote, E. J. (1977). Adaptation of the alpha particle instrument for penetrator mission. In *Reports of Planetary Geology Program, 1976-1977.* NASA TMX-3511, p. 258.)

PREPROTOTYPE SAMPLE ACQUISITION SYSTEM FOR A PENETRATOR



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