ATSS-10

Technical Memorandum No. 33-241

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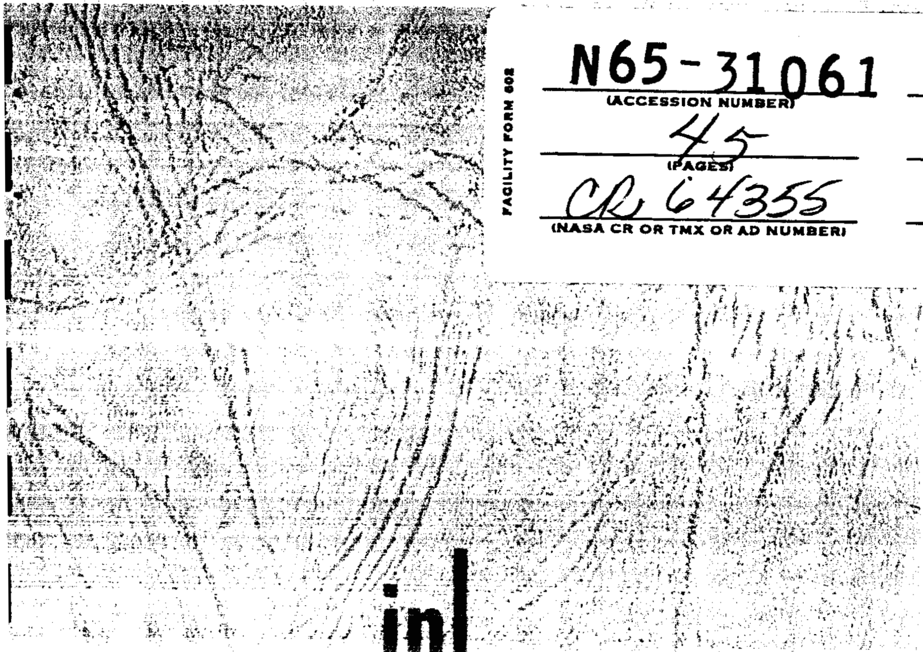

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July 15, 1965

Prepared Under Contract No. NAS 7-100
National Aeronautics & Space Administration

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ABSTRACT

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The utility of unmanned lunar survey probes of the *Ranger* or *Surveyor* class in the post-*Apollo* scientific exploration program, *Apollo Extension Systems (AES)*, is defined. Missions, measurements, instruments, probe types, and probe requirements are evaluated, and priorities are established. It is shown that the most important role for unmanned probes is one of widespread reconnaissance which attempts to define and amplify broad lunar problems and to delineate the most significant areas on the Moon for subsequent, detailed investigations by manned vehicles.

Author

I. INTRODUCTION

A. Scope of the Investigation

The objective of this report is to define the utility of unmanned *Lunar Survey Probes (LSP)* of the *Ranger* or *Surveyor* class in the post-*Apollo* scientific exploration program, *Apollo Extension Systems (AES)*. Three specific questions regarding Survey Probes are addressed; they are:

1. What are the missions for which probes would be employed relative to the scientific exploration roles of other spacecraft planned for the *AES* program (*viz.*, manned landers, manned mobile vehicles, and manned orbiters)?
2. What are the scientific measurements to be made by the survey probes and what instruments are best for each measurement relative to their development status?
3. What type of probe is most suitable for exploration in the *AES* program, and what requirements are placed on the probe?

The study presented herein was requested by F. Roberts of the Office of Manned Space Flight (OMSF) as part of a broader effort aimed at defining the nature of unmanned vehicles for the *Apollo Site Survey* program. This program is designed to provide the *Apollo* lander with a certified lunar landing site in case the preceding unmanned site selection program does not delineate a suitable site by *Apollo 1* flight time. The *Apollo Site Survey* program is, thus, a backup effort; the program is planned to consist of concomitant *Apollo* orbiters and unmanned probes (*LSPs*) which will be ejected and tracked from the orbiters. The orbiters will provide continuous, remote detection of lunar surface, whereas the ejected probes will give *in situ* measurements of terrain character and landing suitability at selected points.

It is logical to consider how the probes of the *Apollo Site Survey* program might be used in the *AES* scientific exploration of the Moon, once the primary objective of obtaining an *Apollo* landing site has been accomplished. If the probes appear to be highly useful in *AES*, the specifications of the probes for this purpose should be considered in the original design and selection of the *Apollo Site Survey* probes. Herein lies the background leading to the study presented in this report.

The given conditions for this study are: (1) The probes should be of the *Ranger* or *Surveyor* or, possibly, *Rover* class. (2) Basic modifications to these vehicles should be modest. (3) A single orbiter, which can be in polar orbit for as long as 28 days, will be capable of carrying several *Surveyor*-type probes, or as many as 20 *Ranger*-type probes. (4) The probes should have flexibility in payload accommodation and operational environment and should be able to operate over a lunation.

Derivation of the specific conclusions to the problems given above requires starting from first principles—in this case, estimation of the state of lunar knowledge at the time of *Apollo-AES* transition and of the scientific observations and measurements, according to their priorities, that will remain to be obtained. The latter considerations then lead to the problem of what sort of exploration program can obtain the desired information most thoroughly and efficiently. The program can be outlined by considering what sort of spacecraft could accomplish each particular, scientific goal, either uniquely or best. The sum leads to an integrated exploration program in which both the value of inclusion of the probes in *AES* and, conversely, the price paid by their exclusion can be assessed. Clarification of the scientific goals that can be best accomplished by probes defines the role of the probe; then, within the bounds of its role, the scientific measurements to be made by the probe are considered. These measurements can be ranked according to their contribution toward fulfilling the role for which the probe is employed. Required instrumentation is then obtained by determining the optimum instrumental method for each high priority measurement relative to the status of instrument development. Lastly, the choice of *Ranger* vs *Surveyor* as the vehicle to be used can be easily made by comparing each spacecraft capability with the role of the probe in *AES* and the measurements to be made. Also derived from this analysis are the requirements for the selected vehicle.

B. Summary of Conclusions

1. Role for Unmanned Probes

A lunar exploration program that is based on a rational analysis of the problem of determining the nature and history of the Moon and that employs a number of different spacecraft, each applied to its best advantage, holds an important role for unmanned probes. The role is, effectively, one of widespread reconnaissance which attempts to define and amplify broad problems, and to delineate the most significant areas for subsequent, detailed investigations by manned vehicles. More specifically, these roles for a stationary probe are those of (1) characterization of representative parts of surface lithologic units delineated by *Orbiter* and (2) the emplacement of apparatus, chiefly seismometric, in a surface net. The unmanned *Rover* has a role in an integrated exploration program of reconnaissance traverses of zones containing discontinuities in surface properties or zones where steep gradients exist in these properties. The chief advantages presented by the probes for reconnaissance are their ability to be placed at virtually any surface point and the expedience of exploration created by the fact that several probes can be carried in one orbiter.

2. Optimum Payloads and Measurements

Eleven important measurements are suggested (Section III B-2) for a combined unit-characterization/surface-net mission of a stationary probe. The soft-lander system has the ability to carry either (1) a minimum-weight assemblage of instruments for this mission or (2) a partial payload of optimum instruments for the measurements of priorities 1 to 6. The latter payload is strongly recommended over the minimum-weight full payload.

The hard-landing capsule as presently conceived cannot provide a useful delivery system except for a *Ranger* 3–5 type single-axis seismometer. Although an increase in capsule volume would allow a larger payload to be carried, it would be at considerable expense in the number of hard-landers per orbiter. The probability of successful scientific results in uncertain lunar terrain is an important consideration in selection of the delivery system; at this stage, the soft-lander appears slightly better than an enlarged capsule because of the possible immersion of the capsule in a soft lunar surface during impact.

The unmanned *Rover*, conceived but poorly defined for the site-certification program, is unsuitable for the role of rover in the exploration program presented here. Some degree of utility can be achieved if the scientific instrument payload weight can be increased by 24 pounds. Site-certification measurements are felt to have little utility in the scientific exploration of the Moon.

II. ANALYSIS OF THE PROBLEM

A. Scientific Exploration of the Moon: Principles and Procedures

Specific recommendations on the employment of *Lunar Survey Probes* should be in accord with a logical overall plan for lunar exploration. It is useful, then, to outline a general approach to the exploration of a planetary body, including systematic procedures for carrying out the program and fixing priorities of investigation. This basic philosophy will form the framework for establishing a comprehensive *Apollo-AES* program and, finally, for defining the potential contribution of a *Lunar Survey Probe* to this program.

The broad goal of exploring the Moon is simply the determination of its constitution and evolution. Knowledge of these subjects not only will allow an understanding of the Moon for its own sake but, also, a great advance in the understanding of the nature and history of the Earth and the solar system. Stated briefly, the immense significance of lunar investigations lies chiefly in the fact that the Moon and Earth represent opposite extremes in the range of volume and density of the terrestrial planets. Because of its relatively small size and low density, the composition of the Moon and the dominant processes which have caused its present state may be very different than those known to occur in the Earth. Consequently, the Moon and Earth might be considered to present boundary values to the processes which have governed the evolution of terrestrial bodies.

The principal problem that follows the acceptance of the Moon as an important exploration goal is that of establishing a logical and systematic exploration program. The way in which a research problem is approached depends, among other things, on how well the problem already has been defined. Where little is understood at the start, initial phases must address a more precise definition of the problem(s) in preference to pursuit of solutions of ill-defined problems. The investigation of largely unknown areas on or within the Earth follows a general exploration plan which contains a rather definite, though flexible, sequence of field observations, field measurements, laboratory measurements, and calculations. These investigations are aimed at defining the critical specific problems for which solutions will most effectively reveal the nature and origin of that area.

In the case of the Moon, we have advanced some small way beyond complete ignorance; but in large measure, we should employ the general exploration plan of defining more precisely the most critical lunar problems, rather than focusing now on either proving or disproving existing theories or statistically oriented investigations. The nature of a systematic lunar exploration program is explained in the following paragraphs.

1. General Basic Steps in Exploration

The first steps in the investigation of the Moon were taken many centuries ago. These were simple observations and notations of the periodic change in the Moon's position and illumination and of the nonhomogeneous surface. With further observations, the orbital characteristics became progressively better known, and the development of the principles of celestial mechanics and the measurements of the Moon's size were followed by the first calculations of the mass of the body. The invention of the telescope made it possible to define more precisely the inhomogeneities on the lunar surface. All of these observations serve to illustrate that the beginning steps in the exploration of any unknown terrain are essentially the same, whether it be that of an island in the Pacific Ocean, a continent such as Antarctica, or a celestial body: the body is defined according to its size, shape, and gross character, its relationship to its surroundings, and its degree of homogeneity.

As exploration progresses, attention is focused on the question of homogeneity. Because this property is most easily measured, an attempt is made first to differentiate the visible terrain on the basis of such features as roughness, smoothness, light reflectance, color, etc.; for the Moon, this stage corresponded to the early delineation of areas of Mare and Terra. This characteristic first step in mapping of a body is followed by a progressively more detailed breakdown of the surface features. But differentiation is not enough. Each area that can be differentiated from another must then be characterized on the basis of as many properties as can be measured. Modern charts of the Moon are made by differentiating and characterizing terrain on the bases of such topographic features as slopes, rate of change of slope angles as a function of distance, relative elevations, and of albedo. Geologic maps of the Moon further characterize the terrain on the bases of crater populations per unit area, stratigraphic position, apparent *freshness* of features (manifested by subtle topographic and albedo effects), color, visible light polarization, temperature, etc. Further measurements and new kinds of measurements will extend our ability to both differentiate and characterize the lunar surface.

At some point in the process of characterizing terrain, it becomes possible to compare and relate the units that have been defined. Categories can be established for units that are similar in character. Categorization allows units to be compared with each other and with known standards. For example, for the Moon it is assumed that the basic laws of physics apply, and that, with caution, some analogies can be made between Moon and Earth features and processes. Such analyzing leads to the definition of specific problems, to the solution of these problems, and to interpretations as to the origin and history of the features. Eventually, by an iterative process, the various interpretations are woven together to produce a unified theory to account for all of the features and parameters that have been recorded, and the composite facts explain the origin and historical development of the entire body.

Exploration need not be confined to the surface of the body if there is some way of measuring internal properties. At present, we know only the general shape and bulk density of the Moon. The same procedure needs to be applied in an exploration of the body of the Moon as for the surface. For example, once the appropriate measurements (e.g., gravitational, seismic) can be made, it will be possible to define density differences in the Moon. These can be *mapped* and characterized in detail, then categorized and interpreted with respect to other pertinent data. This is just an extension of the surface exploration procedure into the third dimension.

2. Specific Steps for Lunar Exploration

At present we have made considerable progress in differentiating, characterizing, and categorizing the visible surface of the Moon. This work, which is by no means complete, has led to the definition of a large number of specific problems which are discussed in detail later in this report. Because we are engrossed in a complex and lengthy exploration program, it is perhaps useful to reexamine the general goals of the program and some of the principles that should govern further efforts.

In the most general terms, the *overall* goals are threefold: (1) to obtain unique answers to the questions we presently know how to state; (2) to synthesize these answers into a unified theory of the origin and history of the Moon, the Earth and, if possible, the solar system; and (3) to be able to define and state the problems we are presently unaware of. The process is, of course, unending, for each new problem requires a solution and, in turn, almost always leads to the definition of further problems.

General exploration procedures follow directly from the above objectives. The exploration program, in addition to further characterizing and categorizing units, should aim to answer specific questions, rather than making random measurements in random places and attempting, for example, a purely statistical analysis. Once the initial problems are defined and priorities established, a plan for obtaining measurements can be carried out. As information becomes available, the problems must be reevaluated and, if necessary, redefined; subsequent measurements must be adjusted accordingly.

This general procedure for exploration demands a flexible program, one in which all means of exploration—with their diverse measurement capabilities—are closely coordinated. Spacecraft payloads that are *frozen,* perhaps for engineering and technical reasons, may become obsolete if the initial exploration data require restatement of the problems and definition of new measurements. Similarly, the overall program will be slowed unless ground and orbital measurements, for example, are closely integrated to maximize data interpretation.

A rationale for scientific exploration of the Moon should also include a basis for determining the priority ranking of problems and their proposed means of solution. It is probably best to separate clearly the scientific importance of a measurement from the technical feasibility and program constraints involved in actually making the measurement. Only the feasible measurements will be made anyway, and some scientifically important measurements may not yet be feasible.

3. Establishing Priorities

Priority should be afforded those problems whose solutions bear directly on a number of other problems. Certain questions, if they can be answered, can provide the key to many others. As an example, the determination of the internal structure of the Moon by seismological measurements could provide information on the thermal history of the body, its internal activity, and ultimately, on its origin and geologic history.

A second basis for determining priority is the degree of uniqueness of the answer obtained. An example is the problem of determining the absolute age of a rock by radioisotope measurements. The uniqueness of a date made from a particulate surface-debris layer on the Moon is probably very low, in view of the possible mixed origin of this material. A sample of bedrock should provide a more reliable and meaningful age date and a measurement in such material deserves higher priority.

A third criterion, which applies to surface measurements, is the degree to which given data can be extrapolated over the Moon as a whole. Experiments that cannot be given priorities on the basis of their probable contribution to fundamental lunar problems or uniqueness, can perhaps be separated in terms of regional interest. Detailed geologic mapping should, for example, proceed at first on the bases of (1) seeking to answer fundamental scientific questions and (2) the applicability to regional mapping problems.

The technical feasibility of an experiment and its relation to other experiments in terms of time and funding constraints should be considered separately from the scientific priorities. This does not mean that the feasibility matters are less important; they ultimately govern what *can* fly. On the other hand, the scientific merit of an experiment should not be confused with how much it weighs or how difficult it is to execute.

4. Major Problems for Lunar Investigation

Listed below are some of the major problem categories at our present state of knowledge of the Moon. Priorities are not attempted here but will be discussed later with specific reference to measurements to be made at *AES* time.

One problem category concerns the *body* of the Moon.

1. *Shape of the Moon and gravitational potential.* Is there a *frozen* tidal bulge pointing toward Earth? If so, what is its height, extent, and age; what is the internal density-distribution of the Moon; is there a departure from hydrostatic equilibrium?
2. *Internal structure.* What internal velocity discontinuities exist; is there a core? If so, is it liquid?
3. *Internal activity.* Are there moonquakes; has there been volcanic activity; what is its nature and source? Is there evidence for orogeny; for convection?
4. *Thermal regime.* What is the surface heat flow; what radioactive heat sources occur in lunar rocks; what is the extent of volcanism in space and time?
5. *Magnetic field.* Does the Moon possess a sensible magnetic field? If so, what is its strength and polarity? Do surface rocks contain remanent magnetization induced by prior internal lunar fields of different strength and orientation from the present one or by some external field?

A second general category relates to the *surface* of the Moon.

1. *Lithologic units.* What is the degree of compositional, textural, etc., heterogeneity of the surface? What is the lateral and vertical distribution of units?
2. *Petrology.* What is the nature and origin of the lithologic units? Are equilibrium assemblages present?
3. *Structure of the surface.* What internal mechanical forces have affected the surface? Is the surface in equilibrium? What is the strength of the rocks; what is the origin of features such as rilles, wrinkle ridges, domes, sinuous valleys, etc.?
4. *Sequence of events.* What are the relative ages or absolute ages of the units? What is the nature of the lunar stratigraphic record; what is the relation to Earth geologic history?
5. *Surface processes.* What processes are active now; in nature, rate, or extent, how do they compare with those in the past? How do these processes affect the surface?
6. *Biology.* Does life exist now at or near the lunar surface? Has it existed in the past; if so, what was its nature, duration, and extent?

A third category of general problems for investigation is that of *cislunar* environment.

1. *Meteorite flux.* What is the present mass, velocity, and frequency of meteorites impacting on the Moon; has this changed with time?
2. *Radiation.* What is the energy spectrum and time-variations of solar and galactic particulate and electromagnetic radiation at the Moon's surface?
3. *Atmosphere.* Is there a lunar atmosphere? If so, what is its total pressure and composition; is there evidence for a more dense atmosphere in the past?

B. Estimated State of Lunar Knowledge at Time of Apollo Extension System (AES)

1. Sources of Information Prior to *AES*

In order to ascertain what data will be needed at *AES* time and, specifically, how the *Lunar Survey Probes* would contribute to data acquisition, it is necessary to estimate what can be found out prior to the beginning of the *AES* program. We cannot determine precisely all the experiments that will be flown and in what order, nor, of course, can we foresee how well spacecraft and instruments will function. But it is possible to cite the probable experiments and, also, the optimum situation, assuming that all instruments function properly. A realistic estimate of our state of knowledge at *AES* time, taking into account certain expectable difficulties, is more speculative, but will be attempted briefly.

There are six potential sources of information about the Moon prior to the *AES* program. They are:

1. Earth-based measurements (including Earth orbital)
2. *Ranger* photographs
3. *Surveyor* spacecraft series
4. Unmanned lunar orbiters
5. First *Apollo* landers
6. *Apollo* orbiters (in support of landers)

Each of these sources of data will be examined below.

a. Earth-based measurements. Earth-based measurements could continue to provide valuable lunar data to *AES* time and, possibly, beyond. Included here are ground-based telescopic measurements and measurements of the Moon from balloons and Earth orbit. Earth-based telescopic measurements, although less spectacular than spacecraft operations, can be made very inexpensively and can be conducted over extended periods of time. By *AES* time it should be possible to measure the lunar photometric and polarimetric properties in considerably more detail and to define the major areal color differences. These properties and others, such as areal temperature differences and areal variations in microwave and radar returns, should be closely correlated with topographic and geologic data. Time and phase angle variations of these properties are well suited to Earth-based observation and could be adequately documented by the end of the decade. Charts and geologic maps, to the scales possible from Earth telescopes, should be completed for the visible portion of the Moon.

Earth-based observations can supply additional important data: namely, information on activity, or lack thereof, on the lunar surface. Observed gaseous emissions, luminescence, or related events have been sufficiently infrequent that it is unlikely to witness such activity during the time-span of a spacecraft operation. On the other hand, it would appear likely that nearly continuous telescopic observations of the Moon over the next five to seven years would monitor some events. If measurements accompany visual observations of future lunar events, it may be possible to add significantly to our meager knowledge of internal activity on the Moon or, perhaps, to what we know about the surface materials.

Measurements of the lunar surface from balloons, small rockets, or Earth-orbital spacecraft promise to expand the scope of the Earth-based telescopic observations. Making measurements from points above most or all of the Earth's atmosphere will permit improved imagery and extension of measurements into the ultraviolet (below about 2900 Å), as well as into the portions of the infrared that are obscured by absorption bands.

Measurements of the Moon from Earth (Earth-based and Earth-orbital) over the next five to seven years will enable further differentiation and characterization of lunar surface properties. These data probably will not lead to unique solutions of the problems of the microstructure and composition of the surface material, but they may significantly narrow the possibilities; these data will certainly provide a much-needed basis for regional extrapolation and correlation of other pre-*AES* measurements from spacecraft such as *Surveyor* and *Apollo*. The possibility appears good of monitoring and measuring some activity on the Moon and, thereby, assessing the extent and nature of possible internal processes. Such data would help to define future scientific missions in terms of measurements to be made and areas to investigate.

b.* Ranger *photographs. The completed *Ranger* program has produced several thousand close-up photographs of the Moon but little agreement among the scientists who have attempted interpretation of the data. Considered from the scientific point of view, rather than with regard to the problems of landing an *Apollo* spacecraft, it appears that the *Ranger* photographs have raised many more questions than they have answered. This does not diminish the value of the photographs for it is at least possible now to state problems that were previously unknown. Answers to some of these problems may be obtained by laboratory studies (for example, can "dimple craters" be created by an impact mechanism), but it appears likely that further investigation of the photography will lead, primarily, to a further refinement of problems to be met by future exploration, and not to simple conclusions.

c. **Surveyor *program.*** The measurements that can be made from a *Surveyor* spacecraft have been discussed in detail in other reports and need not be repeated here. As presently planned, the initial *Surveyor* payloads and missions are designed to achieve engineering objectives. Primary considerations are those of achieving a successful soft landing and spacecraft operation, and of certifying a site for the first *Apollo* landing.

If all of the *Surveyor* spacecraft are employed for the engineering mission, the scientific byproduct will consist of some information on the close-up geometry and character (photometry, grain size, cohesion, layering, etc.) of one or more small portions of the lunar surface. Viewed in the context of the major scientific problems of the Moon as a whole, these contributions would be modest.

If little difficulty is encountered in the operation of the first few *Surveyors* (1–4 as now planned), and it is possible to satisfy the *Apollo* requirements early in the *Surveyor* program, there is the probability of conducting additional, scientific experiments. The scientific experiments under consideration for flights 4–8 are: a lunar seismology experiment, compositional determination by an alpha-scattering device, and a micrometeorite experiment.

The seismometer, a short-period vertical-component instrument, could record moonquakes and meteorite impacts and thereby provide valuable information about internal activity and lunar structure beyond the immediate vicinity of the spacecraft. Simultaneous operation of two or more seismometers at different locations would provide maximum information by locating moonquake epicenters and permitting a more detailed structural analysis.

The alpha-scattering experiment could provide information on the kinds and abundances of certain elements in the lunar surface material. In spite of the difficulties and ambiguities inherent in this experiment, it could deliver the only data on lunar surface composition (other than the data from the first *Apollo* landings) prior to *AES* time. The lack of supporting experiments (such as mineral-phase determination) to facilitate interpretation of the alpha-scattering data, the problem of sampling meaningful material, and the limited number of data points (maximum = 4), however, leave uncertainties as to the ultimate scientific value of the experiment.

The micrometeorite experiment is intended to measure the flux, momentum, and size distribution of particles impacting at a given *Surveyor* landing site. This information could substantially improve our knowledge of the erosion-redistribution mechanism presently thought to operate at the lunar surface.

d. Unmanned orbiters. The unmanned orbiters are designed to provide high resolution imagery of portions of the Moon. In theory, the entire Moon could be charted by a polar orbiter in this manner. One of the major scientific contributions of the orbiter program could be to supply information about the side of the Moon that is not visible from Earth. Evidence for anomalous features or processes on the back side of the Moon would be important in planning future exploration, and in determining how representative Earth-side measurements are of the Moon as a whole. The specific scientific results of high resolution imagery (30-ft resolution at 200 mi, 3-ft resolution at 20 mi altitude) are, however, difficult to assess in advance.

First priority for the orbital flights will be photographic coverage of the *Apollo* landing belt between 10°N and 10°S and 60°E and 60°W. It seems probable that orbiter coverage of this and other areas will lead to the definition of many new scientific problems but to the solution of few, except where ground data from the scientific *Surveyor* or the *Apollo* landings are available. One set of scientific measurements that will be possible from the orbiter images will be widespread crater-statistics. These measurements will place the crater counts from the *Ranger* and *Surveyor* photographs in context with the surrounding regions, and may lead to a firm knowledge of impact statistics for the entire Moon. In addition, the images will permit detailed categorization of the surface on the basis of reflectivity and fine-scale topography. This will serve as a basis for most of the scientific measurements to follow.

The unmanned orbiter may also carry a micrometeorite detector and a gamma-ray spectrometer. The micrometeorite device would add more data on influx statistics. The spectrometer, if flown close enough to the Moon to detect gamma radiation, could determine the abundance of K^{40} (and possibly U and Th) and map areal changes in this parameter. A high concentration of K^{40} (and, therefore, K) in the surface rocks would suggest a compositionally differentiated Moon.

e. First **Apollo** ***landers.*** The most significant advance in our knowledge of the Moon will probably follow the collection and the return to Earth of lunar rock specimens, which can then be analyzed and measured in detail in the laboratory. Equally as important as the specimens, themselves, is the fact that the geologic setting of the collection locality will be known. The landing site will have been photographed at high resolution, it will have been investigated by at least one *Surveyor* spacecraft, and the astronauts who do the collecting will be able to describe the landing site.

f. **Apollo** ***orbiting vehicle.*** The portion of the *Apollo* spacecraft which remains in orbit while the *Lunar Excursion Module (LEM)* descends to the lunar surface is a potential platform from which to conduct scientific experiments. The time available for such activities is perhaps limited, but it may be possible to obtain some very high resolution photography of preselected features, or to photograph areas of interest not covered by the unmanned orbiter.

2. Integrated Knowledge of Moon at *AES* Time

The beginning of the *AES* program requires that at least one, and perhaps a few, *Apollo* landings will have been achieved previously. The *Apollo* landings, in turn, require at least one successful engineering-*Surveyor* landing to verify the site, and at least one successful orbital mission (unmanned or manned) to provide high resolution photographic coverage of the landing region. These requirements define a possible minimum program for producing scientific information. The maximum information would come from a complete pre-*AES* program having no spacecraft or instrument failures.

The minimum pre-*AES* program would offer only one source of scientific data measured at the lunar surface itself, namely, that determined by the first *Apollo* astronauts. Although not designed as a scientific mission, the *Apollo* landings are a potential source of important data, especially if lunar samples are successfully returned to Earth. Data from the other sources will be primarily engineering (as in the case of the *Surveyor* site certification mission) or photographic-TV from *Surveyor* and the orbiting vehicles. (A significant exception might be the orbiter micrometeorite and gamma ray measurements.) Taken together, the Earth-based measurements and the various spacecraft photographic-TV missions are probably capable of further defining lunar problems and of differentiating and charting the terrain, but it is unlikely that any (or many) problems will be uniquely solved. The importance of the *Apollo* sample-return mission would then be strongly emphasized. The *Apollo* samples can supply complete data on rock phases, composition, equilibrium, age, physical properties, etc. for the limited collection localities. The landing(s) would also provide the first opportunity to place a seismometer on the lunar surface.

In the event that the maximum pre-*AES* program is achieved, there will be far more complete imagery of the Moon and up to four scientific *Surveyors*, in addition to the *Apollo* landings. The relatively incomplete compositional analyses (by the alpha-scattering experiment) would be enhanced by the possibility of comparing analyses at four separate localities to test for chemical variations. Areal changes in bulk chemistry could perhaps then be tentatively correlated with properties measured from Earth and as seen in the spacecraft photography. When coupled with the complete analyses of the *Apollo*-returned samples, it should become possible to determine whether or not gross chemical variations occur on the Moon, and to draw conclusions as to their nature.

In a maximum pre-*AES* program there would also be a definite answer to the question of the existence of seismic activity on the Moon. Up to four seismometers placed by *Surveyor* spacecraft, and one or more placed by *Apollo* astronauts, depending on the simultaneity of their operation, could form a net that would be adequate to define most of the major internal structures of an active Moon.

The maximum program would also combine micrometeorite measurements at the lunar surface (by *Surveyor*) with high resolution imagery of large areas and additional micrometeorite measurements by orbiters, to permit an integrated picture of the extent, nature, and effects of meteorite impact on the Moon.

What will actually be known at *AES* time will probably fall between the possibilities for the minimum and maximum cases. The anticipated difficulties in soft-landing the *Surveyor* spacecraft, however, suggest that the scientific *Surveyor* payloads may not all be flown, in which case the number of Moon-based scientific measurements would be significantly diminished. This would shift the total state of our lunar knowledge near the minimum side of the scale and emphasize the need for ground-based scientific measurements in the *AES* program.

C. Further Data Required at AES Time

Prior to the beginning of the *AES* program, scientific experiments will have been a relatively minor part of the lunar exploration program, in comparison with the goals of landing a man on the Moon and developing the technology necessary to do this. The scientific data required at *AES* time will depend in part on the scientific byproducts of the pre-*AES* programs, and in part on the rationale that is established for *AES* exploration. We have treated both of these factors in the previous sections and will now discuss measurements (following the outline of problems listed in part II B) that will probably be needed as the *AES* program begins.

1. Body of the Moon

a. Shape and gravitational potential. It is probable that pre-*AES* orbiting vehicles cannot be tracked sufficiently accurately for selenodetic measurements. Consequently, the definition of a lunar gravity potential will probably remain for the *AES* program. Furthermore, the precise shape of the Moon will probably not be certain by *AES* time. The shape might be investigated by reference of lunar surface points to the celestial sphere or by tracking of movement of points marked by some signal observable on Earth during lunar librations. The degree of departure of the lunar body from hydrostatic equilibrium may grossly indicate the current strength of the Moon; it further could suggest the position of the Moon relative to other bodies with which it is in equilibrium.

b. Internal structure. If the Moon is seismically quiet or if seismic measurements are not made by *Surveyor* or *Apollo*, an important requirement of the *AES* program will be to make seismic measurements at several localities to search for the presence of major velocity discontinuities. A quiet Moon will, of course, require an active seismic experiment. Study of a core may require that seismic stations be established on opposite sides of the Moon. The investigation of near-surface structures, such as variations in the depth of the maria material or the thickness of rubble surrounding large craters, will call for as many seismic stations as practicable. Heat flow, gravity, and magnetic data, also, can supply information on internal structure and should be integrated with the results of the seismological studies. These measurements are discussed in other sections.

c. Internal activity. If any seismometers operate prior to *AES*, we will probably be able to determine whether the Moon is active or quiet. The discovery of an active Moon, either pre- or post-*AES*, would justify an *AES* investigation of the nature and extent of this activity. Recent estimates of meteorite flux for the Moon suggest that large impact events are sufficiently rare that they probably would not constitute an important source of seismic activity over periods of a few weeks or months. Sensitive instruments, however, might record nearby small impact events. Internally-generated moonquakes would be of more significance to the problems of internal structure and processes. Knowledge of the energy, frequency, location, areal density, etc. of quakes would contribute to a picture of the internal structure and the nature of tectonic activity. Tremors associated with volcanic activity, thermal "noise," and microseisms should also be monitored.

d. Thermal regime. The *AES* program will provide the first opportunity to study lunar heat flow. These data, interpreted in light of other information such as internal structure, seismic activity, density distribution, radiogenic heat of the surface rocks and petrologic evidence for differentiation, will be of prime importance in deciphering the thermal history of the Moon. At this stage of knowledge the absolute value of lunar heat flow in comparison with Earth average is most important; secondarily, differences between maria and terra heat flows may be of interest. High heat flows from young craters (e.g., Tycho) may add to interpretations of their age and mode of formation.

Heat flow measurements should be made at sufficient depths below the surface to avoid the effects of temperature fluctuation with the lunar day and night. This will probably require drilling a hole at least ten meters deep, but will depend on the nature of the surface materials. Temperature gradient and thermal conductivity must be measured at each site; sites should be selected after consulting available seismic or other structural data if there is a choice of location.

Investigation of the lunar thermal regime also calls for a study of past and present radiogenic heat sources in the surface rocks. Samples returned by the first *Apollo* missions should yield basic geochemical data on the abundances and isotopic composition of K, U, Th, Pb, Rb and Sr. By *AES* time we should have a picture of the abundances of radioactive elements for one or two localities on the Moon in comparison to the Earth and various types of meteorites, but it will be necessary to extend sampling to several lunar areas, especially if a compositionally heterogeneous Moon is discovered. A representative picture of lunar radiogenic heat sources along with the abundances of rare-earth elements should tell us whether the Moon has melted or differentiated, and to what extent.

Evidence for volcanic activity, past or present, will bear heavily on the problem of the Moon's thermal regime. Determination of the distribution of volcanism in space and time is basically a matter of geologic mapping. Of particular interest will be the possible relationship between large impact events (e.g., Mare Imbrium ?) and the onset of widespread volcanic activity.

e. Magnetic field. The magnetic field at the Moon's surface contains several potential components, a permanent field generated within the body of the Moon, a field owing to the solar plasma, and a dipolar field induced in the Moon by the plasma field. It may be possible to determine the intensity, orientation, and polarity of a steady internal lunar field if long-term magnetic measurements are made at two or more widely separated points on the lunar surface. The rate of decay of the induced field from the solar plasma is a function of the electrical conductivity of the interior of the Moon. The electrical conductivity, in turn, depends on internal temperature gradient. Magnetic observations thus may throw light on internal lunar structure either by indicating a permanent field which would suggest a lunar core or by providing data from which a temperature gradient could be calculated.

2. Surface of the Moon

a. Lithologic units. The need for differentiation of lunar terrain and the characterization of given units on the basis of properties such as structure, texture, albedo, color, composition, age, etc., will probably continue for as long as we investigate the Moon. (Even the United States, to say nothing of the Earth, has not yet been completely mapped geologically.) Mapping of lithologic units on the Moon in as much detail as possible should be an important goal of the *AES* program. In the previous chapter it was concluded that characterization of units prior to *AES* time would consist largely of measurements by remote means, and that there would be relatively few data points on the ground. The *AES* program should, therefore, effect a balanced exploration plan whereby remote measurements (from Earth and from lunar orbiters) are keyed to measurements on the lunar surface. Nearly all of the presently conceived physical, chemical and imagery experiments will serve to characterize the lunar surface lithology to some degree. Measurements made at the surface, however, are especially important because they are capable of being relatively unambiguous, and because these measurements are required for interpretation of most of the remotely gathered data. Physical properties of the surface that will aid in interpretation of remote sensing data include bulk density, porosity, dielectric constant, thermal conductivity and specific heat. Magnetic susceptibility and remanent magnetism will also be necessary for interpreting present and past magnetic field data.

b. Petrology and geochemistry. By *AES* time a detailed petrologic and geochemical study of the *Apollo* samples taken at one or two points will have been conducted. Many problems will remain to be solved by the *AES* program. We will want to know if the *Apollo* samples are representative of large areas and, also, to what extent the conclusions drawn from these samples can be correlated with regional lithologic mapping by remote sensors. This objective will necessitate measurements of rock compositions, mineral phases, elemental oxidation states, bulk densities, radioactive and stable isotopes, textures, fabrics, etc. at numerous locations on the lunar surface.

We will also want to know how petrologic and geochemical data vary as a function of depth as measured in drill holes at given sites. The rocks near the Moon's surface are the most accessible record of the history of the Moon, and it is probable that most rock bodies on the Moon, as on Earth, occur in layers whose normals are approximately parallel to g. The age of formation of the layers should increase with depth if the principles of Earth stratigraphy apply to the Moon. The constitution or petrology of each discrete rock body provides data from which the thermodynamic and mechanical conditions attending formation of that body may be interpreted. Integration of the stratigraphy and petrology with depth, then, can indicate the nature of past lunar processes and the sequence in which they occurred.

It is entirely possible that the first *Apollo* samples will consist of comminuted rubble which has been derived from diverse sources, and which does not represent an equilibrium of phases. Petrologic and geochemical conclusions would be severely restricted in this event, which condition places heavy emphasis on the need for bedrock sampling in the *AES* program.

The need to measure vertical changes in rock character, and the possible difficulty in obtaining bedrock samples in the first place, suggest that the *AES* program include the capability to drill deep holes—at least to a few hundred feet.

c. Structure of the surface. Most of the major surface structures will have been defined prior to *AES* on the basis of various television and photographic experiments. It will be important to achieve complete imagery coverage of the Moon to permit a full knowledge of the spatial distribution of each kind of structural feature. Structures such as faults, rilles, wrinkle ridges, craters, domes, sinuous valleys, etc. can be mapped in detail by orbital imagery and set in a geological context by reference to the measurements which characterize lithologic units. A fundamental understanding of the forces that have produced the various structures will require the integration of data on the lunar internal structure and activity, thermal regime, petrology, and surface processes. From these data it may be possible to determine the nature and extent of orogenic activity on the Moon, the strength of lunar rocks, and the degree of isostatic compensation of lunar mountains and craters.

d. Sequence of events. Reconstruction of the history of the Moon requires that a systematic time framework be established, not only to relate events on the Moon to each other, but also to relate them to the history of Earth and, perhaps, the solar system. A general system for establishing the relative ages of lunar features based on the superposition of strata, the degree of darkening of crater ejecta, the degree of erosion of crater rims, and the crater population of a surface, has been developed by Shoemaker. This approach has been used with considerable success to interpret Earth-based photographs, and it is anticipated that the principles will be used in pre- and post-*AES* exploration. In addition to relative dating, a goal of the *AES* program should be to achieve as many absolute-age dates of bedrock material from diverse areas as is possible. Radioactive dates are needed to provide an absolute reference for the relative ages and to provide a check on the sequences of events determined by stratigraphic methods.

e. Surface processes. Prior to *AES* time, it may be possible to establish direct evidence for some lunar surface processes such as meteorite impact and material transport. To fully understand these processes and other more subtle ones, such as surface darkening by solar energy bombardment, radiation damage of silicates, luminescence, etc., probably will require extended observations at the lunar surface. Tectonic and volcanic processes may not be presently active and may, therefore, require study by the mapping and measuring of past effects. Both the detailed surface mapping and the extended observations at the surface are well suited to *AES* capabilities.

f. Biology. Return of the *Apollo* specimens of lunar material will give the first evidence on lunar biology. If life or life-related compounds are discovered, there will be a clear need to include further biologic experiments in the *AES* program. In any event, it will probably be desirable to conduct a search on the lunar surface for past and/or present organisms.

3. Cislunar Environment

a. Meteorite flux. Prior to *AES* time some measurements of micrometeorite flux will have been made by *Surveyor* and/or an unmanned orbiter. These measurements will extend over a period of days, possibly weeks, and will involve relatively small recording panels. At *AES* time the need and opportunity will arise to place detectors at the surface which can operate for periods of several months, or even years; such units will have very large panels, in order to give improved impact statistics. Measurements made by such instruments would be capable of recording any periodic or unusual departures from a *normal* impact flux which might accompany the Moon's sweeping through clouds of particles. An accurate knowledge of the present influx rate and character, when compared with measurements and interpretations of the effects of impacts on the surface in the past, may answer the question of how past activity compares with the present.

b. Electromagnetic and particle bombardment. Further statistical data on the energy and particles received from the Sun and space will be required at *AES* time. Long-term measurements using sophisticated equipment will be both desirable and possible. In addition to determining the energy and particle fluxes and their temporal variations, it will be possible to study the effects produced on both natural and artificial materials. The nature and cause of a darkening process on the lunar surface can be investigated directly in this manner. Other phenomena such as the excitation of luminescence by proton bombardment and ultraviolet radiation should be investigated. Once the effects of the present radiation and particle influx are known, it may be possible to measure past effects recorded on the Moon and, thereby, to understand how the output of the Sun has changed over geologic time.

c. Atmosphere. Little will be known of the extent and nature of any lunar atmosphere prior to the *AES* program. Measurements will be needed to define a *steady* atmosphere state, and any areal or temporal departures from this state. These might be caused by local volcanic or degassing activity. The need to coordinate these measurements with geologic investigation is clear. Again, a knowledge of the present atmosphere will assume more importance if it can be compared with past conditions. Evidence for a past atmosphere may be recorded in the lunar stratigraphic record.

III. EVALUATION OF UNMANNED PROBES IN AN INTEGRATED *AES* EXPLORATION PROGRAM

Previous chapters of this report summarize what we believe to be the state of lunar knowledge at the beginning of *AES* time and what data on the nature and history of the Moon will remain to be obtained by the *AES* program. This chapter addresses the problem of how the *AES* program might best obtain these data with a view toward providing a logical derivation of the utility of *Lunar Survey Probes* in *AES*. We attempt here to delineate the spacecraft capability that could accomplish each broad scientific goal best, or perhaps, uniquely. In this way, the role of each spacecraft in an integrated *AES* exploration program can be defined, and the relative value of each role to the program can be weighed.

A. Roles of Possible Spacecraft

Following are the kinds of spacecraft capabilities that have been prominently mentioned for the *AES* program:

1. Stationary manned lander, with either short-term (few days) or long-term (one week → permanent base) capability
2. Manned (± unmanned) orbiter
3. Mobile manned surface vehicle
4. Probe (≡ unmanned surface lander), either stationary or with roving capability

The roles of each of these spacecraft in a program which employs all of them are discussed below; a summary appears in Table 1.

1. Stationary Manned Lander: Short-Term

Short-term manned landers are those in which total lunar staytime is of the order of a few days or less; man-hours of exploration would be a factor of three or four less than the staytime. The limiting radius of exploration would be small, perhaps 1 kilometer.

The *chief goal of a short-term lander* should be the investigation of area-dependent variables which can be examined or measured by astronauts in a manner significantly better than by unmanned spacecraft. The composition of the Moon's surface very probably is not uniform but varies with position on the surface and may be classed as an area-dependent variable. To understand the nature of the lunar surface, and by inference, the composition of the subsurface, the surface must be investigated at many places. The measurements to be made in defining the nature of the surface and subsurface, however, should be ones which can be done best or uniquely by an astronaut, since it would be less expensive to employ an unmanned probe for a set of measurements that could be done identically by both manned and unmanned landers. The small field time further differentiates the role of the short-term manned lander.

In this context the primary goal of this spacecraft should be the collection and return to Earth of meaningful lunar specimens taken with a reconnaissance survey of the geology of the area. The specimens are exceedingly important because they will provide a detailed understanding of the petrology of the small area covered for comparison with similar data taken at other places, and for reference data to which less precise measurements made by unmanned probes can be keyed. An astronaut provides a unique specimen collection mechanism because he can move to difficult terrain where lunar bedrock specimens would be most likely to be obtained and where unmanned probes may find difficulty in reaching. While obtaining samples, an astronaut can be selective and acquire samples of the most prevalent materials, as well as those which are of mineralogical and textural extremes. Further, he can sample lunar materials in relation to structures.

Table 1. Scientific roles and characteristics of vehicles in an integrated lunar exploration program

Spacecraft	Roles	Requirements												
		Reconnaissance vs detail	Radius of exploration	Local mobility	Human scientific judgment (i.e. unfamiliar decisions)	Degree of problem definition required (reconnaissance vs detail)	Position in sequence of logical program	Need to reach all points on surface	Landing accuracy relative to designated scientific point	Exactness of knowledge of measurement positions	Continuity of coverage (over km^2)	Payload	Time/ measurement set	Need for instrument monitoring by men
Short-term stationary manned lander	1. Collection of specimens for return	Recon	$<$ 1 km	High	Mod	Mod	Early	None	Not great	High	0	Low	Hours	None
	2. Investigate simple, local well defined surface problem	Both	$<$ 1 km	V. high	Mod	High	Early	Mod	Mod	High	0	Low	Hours	None
Long-term stationary manned lander or base	1. Measurement of time-dependent phenomena [passive seismology, magnetics, radiation, meteors, surface processes]	Detail	0	Slight[a]	Slight[a,b]	Slight	Any	None	Small	Mod	0	High	Months	High
	2. Detailed field and lab study of small, critical area	Detail	$\leq$ Few km	V. high	High	Mod	Middle	None	Mod	High	0	High	Month	?
	3. Heat flow	Detail	0	Slight[a]	Slight[a]	None	Late	Prob. none	High	High	0	V. high	Month	High
	4. Vertical petrology and stratigraphy	Both	0	Slight[a]	Slight[a]	None	Late	None	High	High	0	V. high	Month	High
	5. Astronomical observations	—	0	Slight[a]	Slight[a]	None	Late	?	High?	V. high	0	V. high	Months	High
	6. Lunar biology or paleobiology	Recon	$\leq$ Few km	High	Mod	None	Early→mid	?	Mod	Mod	0	Slight?	Weeks	?
	7. Experiments in physics or biology	—	0	Slight[a]	Slight[a]	Mod	Late	None?	?	?	0	?	Months	High
Orbiter	1. Mapping	Recon	∞		Slight	V. slight	Early	High	—	V. high	Complete as poss.	High	Month	High
	2. Selenodesy	Recon	∞		None	None	Any	V. high	—	V. v. high	Complete	None?	Month	—
Manned mobile vehicle	1. Detailed surface investigation across zones of rapidly changing properties or discontinuities	Detail	$>$ 10 km	Mod	High	High	Mid→late	Mod	Slight	High	Continuous	High	Days/point mo/trav.	Slight
	2. Measurement of properties critical to interpretation of orbiter data along a flight line	Detail	$>$ 10 km	Slight	Mod	Mod	Any	Slight	Slight	V. high	Point	Mod	Days/point mo/trav.	Slight
	3. Subsurface structural mapping	Detail	$>$ 10 km	Slight	High	High	Mid→late	Mod	Slight	High	Continuous	High	Days/point mo/trav.	Mod
	4. Investigate areally concentrated, complex surface and subsurface, specific problems	Detail	$>$ 10 km	High	V. high	V. high	Mid→late	Mod	Slight	High	?	High?	Days to weeks	None
Probe lander	1. Characterization and correlation of each unit	Recon	0	V. slight	0	Mod	Early	High	Mod	Mod	0	Mod	Days	None
	2. Emplacement of apparatus in surface net [*viz.*, seismometers]	Recon	0	V. slight	0	Slight	Early	High	Mod	High	0	Mod	Months	None
	3. Measurement of properties critical to interpretation of Orbiter data in each unit	Both	0	V. slight	0	Slight	Early	High	Mod	High	0	Mod	Days	None
Probe lander with rover	1. Reconnaissance of zones of rapidly changing properties	Recon	$\leq$ Few km	Slight	Mod[c]	Mod	Early	High	Mod	High	Continuous	Mod	Weeks	None
	2. Reconnaissance of polar and backside areas	Recon	$>$ 10 km	Mod	Mod	Mod	Early→mid	High	Mod	High	Continuous	Mod	Weeks	None

[a] Mobility and judgment in selection of optimum point for emplacement of equipment.

[b] Instrument calibration, monitoring, repair.

[c] By Earth or *Orbiter* control.

The emplacement of instruments for *passive* geophysical measurements which are not basically area-dependent should be of lesser priority on short-term manned landers because of the principles given above, and because they can be done better either on longer-term landers or at a base where their operation can be monitored by man and the instruments can be kept in calibration and repair.

Another type of area-dependent variable, like surface composition, is that of the nature and origin of lunar-surface morphological features or structures. Investigations of features or structures will probably require both mobility and *in situ* judgment as to what path to follow and what constitute the most significant observations per unit time. The basis for such decision probably cannot be made prior to arrival at the site.

There may be certain lunar-surface morphological or structural features at specific places which form well-defined problems by *AES* time; that is, evidence on the nature and origin of the features at a certain surface position may provide a significant increase in our understanding of lunar processes (or, conversely, limit the number of possible lunar models) or may form a critical link in the lunar stratigraphic scale.

Investigation of such problems could well be done by short-term landers if either the problem area is very small or if for a larger area (but $r \leq 1$ km) an exceedingly specific set of questions can be placed with the astronaut before launch. There should be a high probability that sufficient data can be obtained during a 12-hr, or less, field operation to provide a near-unique solution to the problem, as defined, to warrant inclusion of this problem as a short-term *Apollo* goal.

It is probable, however, that most places where a specific problem can be defined from Earth will not satisfy the *Apollo* requirements for landing.

2. Stationary Manned Lander: Long-Term

a. General. Long-term landers will allow men to stay on the lunar surface for more than a few days. The chief benefits to be derived from this longer staytime are:

1. The variety of measurements that can be performed, each of which may require more than one man
2. The larger radius of exploration that is made possible
3. The monitoring of long-term instrument operations
4. The exercise of judgment by the astronaut-scientist relating to problems to be investigated and to time-sharing
5. The time for setting up complex apparatus

At the other limit, the long-term stationary lander would form a permanent base.

The following listing introduces the general investigations which we believe can be done better by a long-term lander or from a base than by other spacecraft:

1. Measurement of time-dependent phenomena (passive seismology, magnetic field, meteors, radiation and lunar surface changes caused by external sources such as erosion, darkening, and transport)
2. Detailed field study of surface petrology and structure of small critical area to form key for reconnaissance studies
3. Lunar heat flow
4. Vertical petrology, stratigraphy, and physical properties in a drill hole
5. Astronomical observations
6. Field studies of lunar biology or paleobiology
7. Experiments in physics or biology in the lunar environment

b. Time-dependent phenomena. Optimum measurements of time-dependent variables require a sufficiently long measurement time for satisfactory statistics and monitoring of the instrumentation to account for non-phenomenological data inputs. It is clear that a group of scientifically trained astronauts stationed for a substantial time at a well-equipped artificial or natural lunar base can best perform measurements of time-dependent variables. Some of these measurements are the following:

1. *Passive seismology.* Detailed knowledge of internal lunar activity can be obtained only from highly sensitive seismometers which have a wide range of natural periods. Such elaborate gear would operate most favorably under constant monitoring, since a minimum operating time should be a month; operating time of a year is preferable for adequate statistics. Further, the set of passive seismic experiments would probably benefit from careful emplacement, perhaps in a covered hole or cave below a zone of thermal expansions and contractions. Location of moonquake epicenters requires seismometer stations at several lunar points.

2. *Magnetic field.* Measurements of the intensity, orientation and polarity of a lunar magnetic field would require long-term observations at several widely spaced locations. Magnetometers for this purpose should be highly accurate (10^{-1} gamma) 3-axis instruments. Because of the elegance of the instrumentation, the extended observations and the need for monitoring and calibration, this experiment could best be performed on a long-term manned lander.
3. *Radiation.* The variations of the energy spectrum of high energy electromagnetic and particle fluxes incident on the lunar surface over an extended (≥ 1 yr) period can be made best at a lunar base. These measurements would supplant the less precise measurements made on earlier spacecraft, would cover previously unmeasured gaps in the spectrum, and would provide an understanding of the long-term time variations. Furthermore, such measurements would serve as a reference for temporal variations in the magnetic measurements as well as changes in rates of darkening, erosion, and other controlled observations of external effects on the surface.
4. *Meteor flux.* A lunar base would clearly provide an ideal location for increasing our precision in knowledge of the meteor flux by both long-time observations and use of screens much larger than can be accommodated on earlier spacecraft.
5. *Time and geometry-dependent surface changes.* The precise interaction between the lunar surface and external phenomena (meteorites, micrometeorites, electromagnetic and particulate radiation) may not be well understood by *AES* time because of the slowness of the changes and inadequate observing time. Certain problems such as darkening, gardening, modes of particle transport, levitation, sputtering, and vacuum-welding of lunar surface materials have been postulated. Early spacecraft will suggest which postulates are most significant, and they may suggest that other processes, currently unknown to us, may predominate.

In general, all surface reactions owing to extralunar phenomena are functions of time, surface geometry, and surface composition. These reactions should be investigated by monitoring either natural lunar test areas which contain a range of geometries and composition or controlled models of these variables at the lunar surface for as long a period as possible. In this way, the nature and rates of predominating effects may be ascertained. As mentioned in preceding paragraphs, the flux and energy distribution of impinging particles and radiation should be measured independently. Both the total length of time and the periodic measurement of degree of change in this investigation mark it as a long-term lander or base candidate.

*c. **Detailed study of small critical area.*** Careful field and laboratory studies of the petrology and structure of one or more small critical areas on the lunar surface should be made so that we understand in detail the geology of certain places which can form references for correlation and interpretation of less quantitative reconnaissance observations taken elsewhere. If possible, the detailed investigation should occur at places where critical relations are known to exist on the basis of previous spacecraft and Earth-based observations. It is probable that such studies would take a group of scientist-astronauts a substantial time period to outline the problem on the Moon, collect sufficient data, field check critical observations and the consequences of interpretations of the data. Considerable analytical instrumentation would probably be required. Hence, the need for a long-term lander or base is obvious for this goal. The radius of the area to be studied in detail should probably be less than a few kilometers.

Besides forming a key with which less quantitative measurements at other places can be correlated, the detailed field study at the base is absolutely necessary for providing a context of the chemical, structural, and temporal nature and history of the surface where other critical base measurements will be made (*viz.*, seismicity, heat flow, magnetics, vertical petrology).

*d. **Heat flow.*** Heat flow measurements will require a drill hole. Because of the heavy and complex apparatus needed in drilling, the probable slowness of penetration, and the time needed for the hole to equilibrate to the lunar ∇T, the heat flow measurement would be done best by a long-term stationary lander or base. Lunar heat flow may be an area-dependent variable such that measurement at more than one location is necessary. It would seem, however, that if more than one or two lunar heat flow measurements are contemplated, some method other than drilling should be considered.

*e. **Vertical petrology and stratigraphy.*** A second set of measurements which requires a drill hole and which is of equal importance to heat flow studies is that of petrology and stratigraphy as a function of depth. These investigations can best be made by obtaining rock core by drilling as deep as possible. The core should be returned to Earth for analysis. The hole should then be logged for significant physical properties. Following a heat-flow measurement, the hole might provide a location for a seismic source with optimum coupling for bedrock transmission.

*f. **Astronomical observations.*** Long-term astronomical measurements in the *AES* program would best be accomplished from a lunar base; a lunar orbiter may provide a satisfactory platform for certain short-term observations.

3. Orbiter

*a. **General.*** Orbiting lunar spacecraft have the important capability of continuous coverage of the lunar surface. For polar orbiters, complete coverage of the surface is possible provided flight time is sufficiently long. This capability suggests two chief scientific goals of the orbiter, mapping and selenodesy.

*b. **Mapping.*** Mapping refers to measurement of certain variables of the surface, near-surface, and lunar fields, continuously as a function of position on the surface. The data obtained can be reduced to contours of equal-values of each function plotted on a surface map or some convenient images. The resulting maps will serve the following potential uses:

1. They might allow interpretation of one or more aspects of the nature of the surface or the body of the Moon, in light of the absolute values of the properties measured. It is actually highly unlikely that unique explanations can be made of orbiter data independently of *in situ* surface measurements because the physical coefficients, the chemical nature, and the very-fine scale surface geometry which control most of the phenomena to be measured will be unknown.
2. The maps may permit interpretation of the nature of the surface by integrating the data from each property mapped, although none could be uniquely interpreted independently.
3. They will allow subdivision of the surface into units characterized by uniformity of values of one or more of the properties mapped, relative to values for adjacent areas. This is an empirical categorization of the surface, and evidence indicating the constitution and origin of the most or even all of the units may be lacking.
4. Maps enable correlation of apparently similar, but discrete, units by either similar values of their characteristic properties or, in the case where no confidence can be placed on absolute values, by characteristic trends of these properties over the units in question relative to those of other units.
5. Maps form a regional base on which the results of surface investigations may be incorporated to provide an optimum geologic context and which can act as an aid to surface navigation.
6. Maps permit delineation of locations of critical surface problems to which landing spacecraft may be sent for detailed study.

Table 2 gives the measurements currently envisaged for an orbiter and the properties of the surface which govern the phenomena measured. Most of these measurements are functions of several variables; the fine-scale surface geometry, composition, porosity, and temperature enter into most of them. Probably none of these variables can be determined independently by an orbiter without surface investigations. However, even if the cause of a first or second order discontinuity in some measurements is not clear, the existence and location of a lateral change is of great importance. We can probably count on the orbiter to furnish, in this fashion, an empirical categorization of the lunar surface into units of quasi-similar properties.

*c. **Selenodesy.*** Selenodetic observations include measurement of the shape of the Moon and the external gravitational potential of the Moon. Knowledge of the lunar gravity field will indicate the internal density distribution and the departure from hydrostatic equilibrium of the Moon. A lunar orbiter appears to be a vastly more feasible method of investigating the Moon's gravity potential than surface work. The accuracy with which the field can be defined, however, depends on the tracking accuracy. The orbit should be low so that higher-order harmonics can be resolved.

4. Mobile Manned Surface Vehicle

Lunar manned mobile vehicles are envisioned to have a large payload capacity, to have a several-month lunar staytime, and to have a range of 100 km. This capability, in theory, integrates all the exploration roles of other vehicles; that is, the mobile vehicle can perform its investigations in as much detail as the stationary lander; it can also perform these measurements continuously across a

Table 2. Orbiter experiments and lunar and cislunar properties which largely control the measurements

Orbiter experiment	Description and objectives	Controlling properties
1. Visible spectral images	Film imaging in several narrow-pass filter ranges for cartography, topography, and surface categorization by areal differences in spectral reflectivity.	Rock composition; oxidation state; particle size and shapes; porosity.
2. Thermal infra-red spectra and images	Concomitant spectrometric analysis of the lunar thermal emission between 8 and 15 μ and imaging at 5–15 μ by an optical mechanical scanner for measurement of lateral variation in surface radiation temperature, temperature gradients, and possibly, mineralogical constitution of the emitting surface by spectral emissivity.	Mineralogy; temperature surface geometry (sub-mm. scale); particle size.
3. Thermal microwave radiometry and imaging	Six-channel radiometry between 0.4 and 20 cm. For radiation temperature measurement as a function of depth (to perhaps 2 meters) possibly indicating depth of thin surface dust layer and its thermal properties. Surface geometric complexity by polarization. Lateral distribution of brightness temperature by single frequency stereo microwave imaging.	Surface temperature; thermal diffusivity as a function of depth; dielectric constant; surface geometry (on scale of wavelength used).
4. Ultraviolet reflectance and luminescence	Filter imaging in UV to extend objectives of visible imaging to broader wavelength range. Spectral photometry in UV may indicate local variations and concentrations of certain elements known to luminesce in the ultraviolet.	Elemental composition.
5. Gamma-ray spectra	Intensity of gamma radiation from naturally-radioactive elements and cosmogenic radioactive elements at lunar surface will indicate abundances of these elements, if detectable. Lateral variance of certain elements will aid in categorization of surface units.	Abundance of K, U, Th; cosmic and solar flux.
6. Radar	Images between 0.5 and 8 Gc over a 40 km swath for surface and near-surface geometry and reflectivity differences over the lunar surface.	Surface geometry (on scale of wavelength); dielectric properties.

region, similar to orbiter, but with the advantage of being able to determine the fundamental properties governing the radiation, as well. The mobile vehicle will have the benefit of scientific judgment of the astronauts which unmanned vehicles will not have.

In practice, however, time provides a limitation to the apparently infinite capability of the mobile vehicle. That is, the exploration of the Moon would take an immensely longer time if the mobile vehicle were used alone than if other types of vehicles were used simultaneously. The other vehicles might not provide as detailed or diverse information as the manned rover, but they could rapidly provide sufficient data to delineate the critical problems for which the rover could be most gainfully employed. In other words, other vehicles can potentially do reconnaissance (which is equivalent to the definition of problems) as well as, and more rapidly than, a manned rover. It follows, then, that the function which the rover can perform, either uniquely or better than other vehicles, is the gathering of detailed data or investigation of a well-defined problem across an extensive area. The mobile vehicle, thus, should not be used for reconnaissance; rather, it should be employed exclusively in investigations which efficiently use its full capabilities.

Within this role of the mobile lander, we suggest the following four prime goals:

1. Linear traverses across zones where either discontinuities or rapid changes in surface properties occur (These zones would be equivalent to contacts, lineaments, etc.)
2. Correlation of surface and orbiter measurements
3. Structural mapping as a function of depth over critical surface units (This is equivalent to conventional exploration geophysics.)
4. Surface and subsurface investigation of well-founded but complex area-dependent problems which require *in-situ* judgment to obtain appropriate data for their solution, and which are concentrated within a single region.

Discussions of these goals follow.

a. Linear surface traverses. The lunar surface units delineated by *Orbiter* will probably be relatively uniform in one or more properties with respect to either the uniformity or mean value of one or more of these same properties in adjacent units. Thus, areas can be chosen within each unit which are most representative of the properties that define the unit; measurements of the lithology and other properties within these representative areas can, thus, indicate to a first-approximation, the character of the unit. It would be possible for these characterization measurements to be made by either a manned or unmanned stationary lander. However, the nature of the contact or gradation between lunar units may not be possible to understand without considerable mobility, detailed measurements (hence, considerable instrumentation), and judgment of scientist-astronauts. The importance of the nature of unit contacts lies in the information they give on the mechanical mode of emplacement of the unit and the sequence relative to adjacent units. The difficulties may arise from the fact that contacts which appear from Earth to be sharp (i.e., ray contacts, maria-continent) may turn out to be transitional zones, kilometers in width. Careful work over a long traverse may be required to define what fundamental properties are changing between units. A traverse by a manned rover along gradients will provide the optimum method of assessing the nature of these zones.

Certain superposed features within a unit or transecting units, such as faults, wrinkle ridges, etc. can be explored to advantage by the manned truck. The vehicle can proceed along a path which can approach most critical observation points per unit time according to the judgment of the astronauts.

In summary, geologic exploration of discontinuities or areas with rapidly varying properties should be done by manned mobile vehicles. The character of relatively uniform areas can be determined by manned or unmanned stationary landers.

b. Properties for correlation with orbiter. A long linear traverse by manned truck across a zone where surface character changes rapidly would provide an ideal opportunity to measure properties of the surface which govern the radiations sensed by the orbiter. From this correlation of surface and remotely-sensed data, it may be possible to make unique interpretations of orbiter measurements at other places.

c. Subsurface structure. The capabilities of the manned truck can provide a superior opportunity for mapping the structure of the lunar subsurface over critical linear or areal traverses. The chief methods would be active seismology and magnetometry; the use of gravity in such exploration is of doubtful value because of the lack of a convenient reference equipotential. In general, the areas discussed in the paragraph above, where surface properties are either discontinuous or rapidly varying, are those in which the subsurface structure might also be expected to be most illuminating with regard to lunar processes and history. Consequently, traverses across these zones by the manned vehicles should employ both detailed surface measurements and observations and subsurface mapping by the methods of exploration geophysics.

d. Specific area-dependent problems. The nature and history of certain lunar morphological features or other problems which are area-dependent can be investigated by the manned mobile vehicle. A similar goal was given for the short-term manned lander, but if a number of such problem areas occur within a region less than a hundred km across, and if each is sufficiently critical to warrant investigation, it may be more efficient to employ a truck to visit each area on single traverse than to send a separate short-term lander to each place.

5. Unmanned Stationary Probe

a. General. Unmanned probes may consist of either hard- or soft-landers. The latter would be of the *Surveyor* class and can have either a payload of scientific instruments or a small roving vehicle. Only the role of the stationary, unmanned vehicles is considered here; the rover is discussed in the next section. The following is entirely general and forms a basis for choice of *Ranger* vs *Surveyor* as the most suitable system at the end of the report.

The role for which a stationary probe should be used is based on its (1) immobility, (2) absence of human judgment in lunar operations and in monitoring instruments, (3) ability to be placed at all points on the lunar surface without concern for return ascent, (4) possible difficulty in knowing the exact location of the probe, (5) ability to be deployed in large numbers simultaneously, and (6) limited instrument capacity. All these characteristics suggest that stationary probes would be useful chiefly in reconnaissance as opposed to detailed work. Because they can be placed at any lunar point, their use should be limited chiefly to the investigation of area-dependent variables or to the function of a delivery system for emplacement of instruments at critical points in a surface net. Their immobility and absence of man, however, prevent the instruments, once landed, from being relocated within a local area to the optimum measurement point. The probes, consequently, must be used at places believed to be relatively uniform.

The utility of the stationary probe capability can be assessed by considering what investigations remain to be done in the *AES* program after those assigned to the spacecraft in the above discussions have been subtracted. Three goals derived in this manner seem well suited to the stationary probes; they are:

1. Reconnaissance characterization of surface units
2. Emplacement of apparatus in a surface net
3. Measurement of the surface properties of significance to orbiter at remote locations

Discussions follow.

b. Characterization of units. The categorization of the lunar surface into some finite number of units by one or more properties is one of the chief steps in the scientific exploration of the Moon. The categorization is in itself not a goal; rather, it is a procedure based on a positive rationale which can lead to an understanding of lunar processes and lunar history. On the basis of Earth-based observations with resolution no better than 1 km, it is currently possible to divide the equatorial region of the face of the Moon into at least nine units, each of which is based on a distinctive set of geometric and visible reflection properties. As presented above, the orbiter is the prime vehicle for the ultimate subdivision of the lunar surface into units of quasi-similar character by virtue of its complete surface coverage and its high resolution-multiple sensor capability. Between now and the time when the orbiter data will be in hand, there will probably be significant advances in the categorization of the face of the Moon.

Lunar processes and history are interpreted from investigations of the materials that compose the unit, the structures that lie within and marginal to the unit, and from the age of the unit relative to that of adjacent units. Thus, once surface units are delineated, prime questions concern the lithology and its variation in each unit and whether discrete units which have fairly similar orbiter properties are correlative or not. It is for these investigations that stationary probes may be used profitably.

Values of the orbiter measurement which are most characteristic of a unit can be contoured; in this way it should be possible to find areas in most units which are representative of the majority of the unit. Furthermore, the places where extreme values occur will be delineated. By sending stationary landers to the average and extreme value points, a first-approximation understanding of the nature and variation of the lithology of the unit can be obtained. Clearly, the confidence given to the characterization of a large (say $10^2 km^2$) unit by a set of measurements at a single point can range widely. The confidence will be a function of the uniformity of the values across the unit as measured by orbiter, the origins suggested for the unit by Earth-based analysis (and respective heterogeneities), and the lithology as measured by the probe itself. As a simple example of high confidence, one might consider a unit defined by uniformly low visible reflectivity, rough surface geometry, microwave temperatures relatively near the IR temperature, relatively high radar reflectivity, and a negligible K^{40} gamma-ray flux; suppose a stationary probe were placed near the center of the unit (to guard against any potential boundary effects) and the investigations indicated a basaltic material. A rather high confidence that the point analysis is indicative of the whole unit would be justified. On the other hand, units which are defined by a completely non-systematic distribution of orbiter values or which can be inferred by other means to be highly heterogeneous, such as ejecta blanket, would provide very low confidence in their lithologic representation by a single point measurement.

The confidence level may be increased in any unit by placing more probes within the unit. As suggested, measurements in one unit at the most representative point and at the two places which are considered extremes (but away from unit boundary effects) should give a good preliminary account of the lithologic nature of many units.

The choice of using probes for the goal of unit characterization relative to manned landers or mobile vehicles should be based on the importance of the unit, the existing knowledge about the unit, and the expected confidence with which a probe could characterize a unit. Certain units in the equatorial region of the lunar face will be the site of manned landings, and it is clear that such manned vehicles will be able to characterize the lithology by specimen return. Further, certain units may be predicted to be of critical importance on the basis of other evidence such that reconnaissance lithogic investigation is not necessary, and the ability for detailed work of a manned vehicle is warranted at the outset. This will probably be true only in near-equatorial areas because of the latitude constraints on *Apollo* ascent. Lastly, some units may simply be too heterogeneous for point characterization, and roving vehicles must be employed. For most lunar units, however, it will be expeditious to use probes for reconnaissance characterization to determine whether sufficiently important problems exist within the unit to warrant sending a manned vehicle there. The probes can also indicate whether certain discrete units with fairly similar orbiter values are correlative. The latter point is exceedingly important in reducing the number of units to which manned spacecraft must be deployed.

c. Surface net. The ability of the probes to land at all points on the lunar surface gives rise to the use of the probes for emplacement of instruments in a surface net. An obvious candidate is a net of simple seismometers which can measure relative arrival times of elastic waves from a large source. The source could be a moonquake or meteorite impact; if neither of these occurs, a large single artificial source or multiple sources might be used. The source might be placed in a drill hole provided by a long-term lander for good coupling, or multiple sources could be created by bombing the lunar surface from the orbiter.

d. Surface properties of significance to orbiter measurements. Measurements of these physical properties of the lunar surface materials which govern the intensity and energy distribution of the radiations measured by orbiter is a possible goal for the stationary probes. That is, if probes are deployed to representative areas in units for lithologic characterization, measurement of critical physical properties of orbiter interest at these places may provide the basis for unique interpretations and extrapolations of the orbiter measurements at other places.

6. Unmanned Roving Vehicle

The unmanned roving vehicle currently conceived for the *Apollo* site selection program is a small device only a few feet long which is carried to the lunar surface by a *Surveyor* and, on detachment, is capable of traveling freely across the surface on wheels or tracks. It can be guided by either programmed automatic control or by real-time control from Earth or, at intervals, from lunar orbit. Communication may either be direct or via a larger transmitter on the parent bus.

A groundrule of this study is that only existing vehicle designs should be considered for a potential probe subprogram in lunar exploration plans. Because no specific rover design has, to our knowledge, been accepted yet, it is difficult to be certain of what missions a rover would be capable. It is well known, however, that the weight allowance of a rover used in the unmanned site certification program is very small, perhaps less than 100-lb total. The scientific payload of a 100-lb rover will consequently be extremely limited, and the range will be small (5-10 km), owing to lack of rejuvenative energy sources. As the payload weight of a soft-landing-rover-carrying bus is increased by ejection from a lunar orbiter rather than from Earth (by weight savings from a smaller retrofuel load), the payload of the rover should also increase. It is not clear, however, whether a 100-lb rover designed for Earth launch could accommodate a larger payload without gross redesign.

We attempt in the following to circumvent obvious confusion by first considering fundamental capabilities of an unmanned roving vehicle and the role any rover might play, disregarding actual vehicle limitations, within the overall exploration outlines in previous pages. The ability of the minimum (100 lb) rover to perform such roles can then be suggested, and as the payload weight, range, and other parameters are varied (without regard to engineering feasibility), the increase in value of an unmanned rover can be assessed. The points contained in the last sentence are discussed in Section III C.

Rover has the obvious property of mobility which indicates that it should be employed for measurement of lateral variation of surface and subsurface parameters and for investigation of specific lunar structural and morphological problems which would require infinite landing accuracy for a stationary lander to reach them. Comparing the ability of manned and unmanned roving vehicles of equal payload weight, lifetime, and range to perform these two tasks, however, the efficiency and effectiveness of the manned vehicle would be superior because of their maneuverability and the quality of data they could provide.

a. Maneuverability. The ability of rover to maneuver on the lunar surface as well as locate and approach closely to objects or features will depend to a large extent on the nature of the terrain it encounters and the accuracy with which it can be guided. Thus the size, weight, buoyancy, and traction of the vehicle must be compatible with an exceedingly wide range of lunar terrain parameters. Similar requirements for a manned rover are less severe since the astronauts can disembark and explore features on foot where terrain is not hospitable to the vehicle. Guidance accuracy for a remotely controlled rover will depend on the visibility obtained with the TV system, and, thus, the quality and field of vision of the imaging system is critical. Furthermore, for realtime guidance of a moving rover from Earth the time-delay in telemetry signals (~3 sec round trip) must be considered in the control scheme. Lastly, several astronauts could simultaneously explore features around the vehicle, whereas the unmanned vehicle must proceed to each feature sequentially.

b. Quality of data. Given infinite time and maneuverability, a very large payload, visible imaging systems equal to astronauts' eyes, an unmanned rover could provide data of equal quality to that of a manned rover. Because these conditions will not obtain and because much of geologic exploration is deductive in the sense of searching for the most critical path with simple yes-no answers being insufficient, unmanned rovers can simply not be considered to provide data of quality equal to that of manned rovers for the two missions mentioned above. The chief role of manned mobile vehicles was given as surface and subsurface mapping across surface discontinuities or along maximum gradients (i.e., contact zones, superposed structures) where delineated by orbiter. The priority of experiments to be performed on a manned vehicle crossing such zones can probably not be specified until some *in-situ* visual analysis of the problem has been made by scientist-astronauts. Deductions as to the major variables across the zone will dictate what measurements should be chiefly employed along the traverse. There is little point in making a pre-set large number of time-consuming measurements which are not critical to the problem at hand. Such flexibility is, of course, not available on unmanned rovers nor will there be a payload capacity sufficient to carry instruments which may be little used as there would be on manned rovers.

These considerations indicate that unmanned rovers would best be employed for preliminary reconnaissance where definitive results are less important than an assessment of the significance and complexity of the problem or else at places where the problem is well enough understood that it is known that the capability of rover and certain experiments can provide definitive results. There is clearly great value of unmanned rovers for such investigations at places on the lunar surface where manned landings and ascents are hazardous. Thus, explorations requiring mobility at polar areas and on the backside of the Moon (no direct communication to Earth) may require the use of an unmanned rover.

Summarizing, we suggest four roles for an unmanned rover with emphasis largely on the first two:

1. *Reconnaissance equivalent to manned rover.* Observations by an unmanned rover across zones of discontinuities or rapidly-changing properties may provide sufficient understanding of that zone that a decision can be made whether that zone is significant enough for detailed investigations by a manned vehicle. That is, unmanned rovers can be used to make a selection of the most critical linear traverses for the manned vehicle. Considering that the latter mission may be two orders of magnitude more expensive than the former, this role seems valuable.

2. *Linear traverses at polar and backside areas.* Examination of certain linear zones at places where manned vehicles are not likely to be sent must fall to the unmanned rovers. The reconnaissance measurements made by rovers can be correlated and compared with detailed surface and subsurface investigations made by manned expeditions nearer the equator.

3. *Specific structural and morphological features.* Well-defined problems involving visual description and specific analyses of certain surface features may be suitable for an unmanned rover to perform. Emphasis would probably be placed on those features which cannot be reached by man.

4. *Lateral extension of unmanned lander measurements.* Rover could extend the surface coverage of one or more measurements from the landing point of a stationary probe. This coud be valuable in assessing how representative the more detailed lander measurements are relative to the surrounding area. The rover might also carry an instrument package away from the bus to an optimum measurement point, for instance, a place away from the area perturbed by the retroblast of the descending soft-lander. Similarly, the rover could move an instrument away from perturbing effects of the bus (a magnetometer, for example).

7. Summary of Value of Probes in *AES* Program

Given simply the comparative scientific capabilities of probes vs other spacecraft, there is really nothing that a probe can do as well as a manned lander or manned mobile vehicle. Considering, however, other factors which have money and time (or efficiency) as their basis, there is a useful, even critical, role for unmanned probes, both stationary and mobile, in the *AES* program. This role is effectively one of widespread reconnaissance which attempts to define and amplify broad problems and delineate the most significant areas for subsequent detailed investigations by manned vehicles. Another way of stating the object of unmanned reconnaissance is that it should provide enough information on the character of the lunar units and features which have been mapped by orbiting vehicles that scientists can determine the most meaningful problems with which and locations from which to investigate lunar processes and history by manned vehicles. Both the manned mobile vehicle and long-term lander have the capability of performing detailed studies of critical, well-defined problems, and it seems inadvisable to employ them in the phase of searching out broad problems (or equivalently, reconnaissance), since such a function does not require their full capability.

Several points combine to make the probe a good reconnaissance tool. The chief virtue is the ability to place a probe at any point on the lunar surface. In addition, the reconnaissance phase will be expedited by the fact that several probes can be carried in one orbiter. Thus, many points could conceivably be measured in one month.. Intuitively, an understanding of the nature of many far-flung points on the lunar surface will be gained in a significantly shorter time period by probe reconnaissance than if a manned mobile vehicle had to travel to each of these points (considering that the expected range of the truck is $\leq$ 100 km). The accuracy or precision requirements for reconnaissance are not great; they are somewhat less than those of which the manned truck will probably be capable. The payload capacity of *Surveyor*, however, should be sufficient to carry needed instruments.

An additional use of the probe is that of transporting and emplacing instruments for a surface net (e.g., seismometers for investigations of the internal structure of the Moon).

B. Probe Measurements

1. Introduction

The objective of this section is to outline the measurements which the unmanned lander and unmanned rover should perform on the lunar surface to fulfill their roles as given in the previous section. It will be recalled that their missions are largely of a reconnaissance nature with the purpose of supplying preliminary description of lunar materials and structures for definition that will permit selection of the most critical problems to which manned landers and mobile vehicles should be addressed. The stationary probe lander has a three-part role:

1. Characterization of surface units
2. Emplacement of apparatus in a surface net
3. Measurement of properties critical to interpretation of orbiter data

The unmanned rover has as its role the reconnaissance of zones of rapidly-changing properties and discontinuities (e.g., contacts, faults, etc.).

2. Lander Measurements

Table 3 presents measurements we consider significant in the role of the unmanned lander. The measurements are identified with the spacecraft roles, and their scientific significance and effective factors are given. These measurements comprise the full range of those which scientists employ for both particular and general investigations of the nature and of history of Earth materials. It should be pointed out that few, if any, points on the Earth's surface or interior have been subjected to measurement of all these properties. Each of these properties, however, plays a potentially important part in lunar investigations in the sense of either controlling the radiation by which lunar units are differentiated or recording the events or conditions under which the unit was formed or subsequently modified.

It is doubtful, however, that any stationary probe can carry sufficient instrumentation to make, simultaneously, all the measurements of Table 3. Consequently, the measurements must be prioritized. The bases upon which priorities can be assigned are as follows:

1. Relative significance to the objectives of the unmanned lander as discussed in Section III A
2. Degree to which properties are independent variables (i.e., some properties may be calculated or inferred from knowledge of one or two other more fundamental properties)
3. Degree to which a property is subject to nonunique interpretation or potential ambiguities by secondary processes, and the consequent need for supplementary information to allow interpretation
4. Feasibility and complexity of making the measurement
5. Accuracy and precision required for significance

Following are comments on measurements listed in Table 3, proceeding from top to bottom within the context given above. These discussions provide the grounds for the selections and priorities of measurements for unmanned landers given in Table 4.

a. Chemical properties. Reading down, the vertical sequence of chemical properties of Table 1 is roughly one of increasing dependence of data upon other knowledge for interpretation. For example, some knowledge of the types of phases that compose the lunar material should precede measurements of elemental abundances, volatile compounds, etc. It does not follow, however, that complete measurement of the phase parameters of the assemblage is a prerequisite to interpretation of the other chemical properties. For general reconnaissance, which is the goal here, phase identification, crude analysis of phase compositions and abundances, and perhaps, elemental abundances largely provide the data from which the nature and history of the material will be interpreted. The importance of volatile compounds cannot be a priori predicted; considerable information on structurally bound volatiles may be obtained by phase identification, but pore volatiles will not be assessed in this manner. Rather high values of dielectric constant and thermal conductivity would be suggestive of high pore H_2O contents. The priority of a discrete measurement for volatile compounds must be assumed to be moderate unless either the unmanned program or early *Apollos* show that it is important.

The abundances of radioisotopes (K^{40}, U, Th) are important as an indicator of possible heat generation in the Moon; values of these isotopes may vary from unit to unit, and this measurement should be a candidate for probes. It is not, however, of primary importance in characterizing a unit and should not be first priority. The ratios of the stable isotopes can be interpreted best when lunar processes are well understood; stable isotope measurements do not fall into the reconnaissance role of unmanned lander. The oxidation state is of considerable importance but may be interpreted from combined phase-cation analyses; if the elemental determinations of O, Fe, Ti, Mn, S, C, and H are sufficiently precise, the oxidation state can be assessed if standard temperature and pressure (STP) equilibrium constants apply on the Moon. The value of average magnetic susceptibility may supply correlative information for the oxidation state of Fe, the valence-variable cation of greatest importance. Because of these potential contributions to knowledge of the oxidation state, a discrete experiment is not of high priority.

b. Geometric properties of lunar substances. Knowledge of the approximate sizes and shapes and the textural patterns of the mineral grains which compose either the solid rock or rock particles which form the lunar surface undergoing analysis is an exceedingly important correlative to the majority of the chemical properties discussed above. Identification of the solid phases in the lunar material comprises the most fundamental lithologic reconnaissance measurement, in that the constitution of the rock is largely understood; but many possibilities of the way in which the rock system formed may remain open. Examination of the textural relations of these materials can provide valuable information for restricting the histories of the rock system. Consequently, textural analysis of the minerals should receive high priority as a measurement.

Similar geometric relations occur among particles of rock which may exist in a lunar surface layer or layers, either unconsolidated or partly or wholly lithified. Each rock particle is probably composed of mineral grains which, within the particle, have geometric relations that indicate the dynamic conditions under which the original chemical system formed (as discussed above). The rock particles, which are derivatives from one or more primary rock systems, in turn have certain geometrical relations that may indicate the way the particulate layer was formed. Thus, the measurement of these geometrical properties, chiefly the particle-size-distribution, is also of importance. The internal textural relations mechanically aggregated rock properties are more indicative of general lunar lithogenetic processes, but the particulate geometry is more significant to the characterization of a particular unit and its physical properties as measured by orbiter and rovers. Consequently, both sets of geometrical properties should receive high priority.

Fabrics in lunar surface material consist of the pattern and orientation of linear and planar elements of the lunar rock that intersect the surface. The fabrics to be considered are generally megascopic; they are of nearly equal importance to the above geometrical properties.

c. Physical properties of lunar substances. Other than remanent magnetism and depth of surface layer, all of the physical properties of bulk surface materials are related within the group and related to the chemical properties of that material. That is, knowledge of the chemical phases which compose the material and of one or two of the physical properties listed will allow either calculation of values for the other physical properties or

Table 3. Possible measurements for a stationary probe

Role	Measurement category	Measurement	Scientific significance	Effective factors
Unit characterization	Chemical properties of lunar substances	Phase-identification* -compositions* -abundances* -ordering -sequence of formation	Indicates fundamental constituents of lunar material for comparison with material at other places and with Earth rocks. Analyses indicate whether system formed in equilibrium or not and the probable thermodynamic conditions which controlled consolidation. Suggests rate of consolidation of system and nature of changes which occurred to system after primary consolidation. Indicates approximate abundances of major elements and their partitioning.	a. Possible dilution by meteoritic infall. b. Possible surface radiation damage. c. If surface is a particulate layer, it is probably disequilibrium mixture. d. Difficulty of measurement increases with depth.
		Elements: Major, abundances ($\geq$ 1%) Minor, abundances ($<$ 1%)	Indicates major composition of chemical system in absence of phase data. Minor elements suggest position in igneous differentiation by correlation with known Earth trends. Adds to data of overall abundances of the elements.	Remarks a. and c. above apply here; these measurements should be accompanied by phase data, above.
		Volatile compounds-identification -abundances -temperature of emanation	Compounds indicate gaseous species which may have controlled consolidation and which species are emanating out of the Moon. Temperature indicates whether pore adsorption or held in solid.	Possible ambiguity of primary or secondary addition of volatiles to solids; also strongly adsorbed gases may be confused with essential volatiles in solid.
		Isotopes: radio, abundances stable, abundances	Comparison of abundances with Earth rocks and meteorites. Heat generation and differentiation indexes; possible lunar thermometry; absolute ages.	Diffusion losses.
		Oxidation state	Independent measurement of lunar oxygen pressure during consolidation; assists magnetic measurements.	Possible reduction by solar protons.
		Metamictization of crystalline phases	Indicate effect of solar protons and ultraviolet on crystalline solids in vacuum.	
	Geometric properties of lunar substances	Mineral grain sizes and shapes* and orientation; particle-size distribution of aggregate; linear and planar fabrics	Evidence of rate of consolidation, discontinuities in crystallization, dynamics during formation. Conditions of sedimentation of particulate materials.	Mostly visual qualitative measurements and interpretations. Problem of references for measurement of orientation.
	Physical properties of lunar substances	Density* (bulk)	Comparison with theoretical density given by chemical phases.	Combines solid density and porosity; problem of layered materials.
		Magnetic susceptibility	Controls intensity of magnetization. Needed for interpretation of surface (or near-surface) magnetic traverses.	Meteoritic Fe may prevent clear understanding of lunar value.
		Remnant magnetism	Magnetization left after removal of magnetization produced from existing lunar field (if any). Shows field strength and orientation of previous field.	Effects of shock, diurnal heating; orientation of specimen required.
		Porosity*	Adds to understanding of sedimentation processes on Moon. Also indicative of gas pressures in lavas.	Difficulty in measurement; problem of layered surface.
		Dielectric constant*	Equals electric permeability. Major factor in radar reflectivity and μ wave emissivity; suggestive of amount of H_2O.	Difficulty in measurement; problem of layered surface.
		Thermal conductivity*	Indicates depth of which diurnal heating can effectively penetrate for μ wave mapping.	Difficulty in measurement; problem of layered surface.
		Specific heat*	Combines with thermal conductivity to control velocity of temperature propogation.	Difficulty in measurement; problem of layered surface.
		Elastic constants	Control, with density, elastic wave velocities.	Difficulty in measurement; problem of layered surface.
		Rupture properties	Coefficients for selenotectonic and impact deformations.	Local properties probably not extrapolatable for wide-scale considerations.
		Depth of particulate layer	Surface erosion, deposition rates, mechanisms; 2+ layer case for orbiter interpretations.	Problem of identification of bedrock.
	Age of formation	Radioisotope ratios	Sequence of lunar unit formation; lunar stratigraphic scale relative to Earth events.	Radioisotope age may be that of some post-consolidation effect; effect of diffusion, heating, shock; should not be measured without geologic context.
	Surface geometry	Morphological expression* slopes, relief	Either primary morphology as indication of mode of formation or emplacement of unit, or as modified by destructive and constructive lunar processes and indicative of those processes. Assess slope stability.	Possible ambiguity of determining primary or secondary morphology.
		Superimposed structures* faults, fractures, folds, craters	Nature of deformative processes on Moon.	
		Lateral variations of topography and reflectivity	Evidence for establishing confidence level of representativeness of measurement point for entire unit.	
	Body geometry	Configuration of subsurface boundary	Three-dimensional body shape; indicates mode and conditions of formation of body.	
Surface net	Internal structure	Seismic wave travel times	Depth of discontinuities by elapsed time from known source; elastic velocities of layers, hence rock types, indicated.	Long-life requirement; must position seismometer and source; need good acoustic coupling.
	Atmospheric variations	Total and partial pressures	Location and understanding of surface vents of escaping lunar gases or gases produced by solar wind interaction with surface.	Spacecraft outgassing source of possible confusion.
Orbiter properties		Properties as given above by * in above notations		

empirical determination of these values by comparison to similar materials on Earth. Consequently, it is our opinion that a discrete measurement for each of these properties should not be considered, but that attention should be devoted chiefly to analysis of the chemical phases of lunar material from which the physical properties are fundamentally derived.

Of these properties, however, porosity is most important because it profoundly affects values of the other physical properties of the lunar surface, and it cannot be derived from knowledge of the phases composing solid parts of the surface. Measurement of porosity is normally difficult, especially in unconsolidated materials. However, a potential method of determining this property is by making an *in-situ* bulk density measurement of surface materials for a depth of, say, one foot (as by gamma log). The solid density can be determined from phase analysis, and by calculation, an approximate value for porosity can be obtained from the two density values. Therefore, a surface density measurement is considered to be of high priority in the company of a phase analysis experiment.

Values of dielectric constant, thermal conductivity, and specific heat will depend, also, on the amount of pore volatiles, chiefly H_2O, if any is present. It seems reasonable for initial probe reconnaissance to assume that the pore contents of surface materials will be negligible or, if non-trivial, that the types and compositions of solid phases will reflect the existence of significant pore fluid content. This problem will be further amplified by the findings of the first *Apollo* astronauts, which knowledge may suggest that a discrete measurement of volatile compounds in the surface materials should be of higher priority than given here. In any case, discrete measurements of dielectric constant and the thermal properties are not recommended for the *AES* probes.

Remanent magnetism is an important, but difficult, measurement. Much prior information concerning the intensity, orientation, polarity, and temporal variations of the existing lunar field is required before remanent magnetism can be interpreted. This measurement is of very low priority for reconnaissance studies by probes.

The depth of the particulate layer or layers may be extremely difficult to measure precisely, because of ambiguities in interpreting what exactly constitutes discontinuities between such layers as would be measured by a downward-thrust prod. Approximate depth(s) may, however, be inferred by examination of the surface morphology and refracted elastic waves, both of which can be performed by other experiments. A discrete measurement of depth of particulate layer(s) is, thus, given a low priority.

d. Age of formation. The absolute age of primary formation of the rock system which forms the unit in question is, in theory, one of the most important measurements that can be made. In practice, however, ages computed from ratios of radioisotopes are subject to ambiguities in interpretation; and, in the absence of considerable supporting information, the meaning of these ages may be completely uncertain. Briefly, the nature of the primary consolidated rock must be known as an initial condition, and all subsequent events which have either modified the rock or mixed foreign materials with it must be understood before the significance of the radioactive age can be evaluated. Knowledge of these factors is critical in order either to decide which event the age represents, or to evaluate whether age, in fact, does represent an event, or, simply, a situation in which the isotope ratios are the result of differential diffusion. Because of the criticality of extensive supporting information to this measurement, it is given a low priority for the reconnaissance role of the unmanned lander.

e. Surface geometry. Images of surface geometry in the visible range are of high priority to provide a context for the analytical measurements, and possibly, to indicate the primary surface morphology of the unit and the effects of later modifications for their own sake, as well as their potential effect on the chemical and physical properties measured. Furthermore, such images of the terrain surrounding the measurement point are critical to the establishing of some level of confidence regarding the degree of representation that the measurement point provides. Knowledge of the surface geometry of the area may supply a key to exact location of the probe relative to visible images of the orbiter. The emphasis in such images should be on good resolution near the vehicle for examination of the surface's fine (down to a few mm) structure. To summarize, the study of images representing the surface geometry is of high priority.

f. Body geometry. The configuration of the subsurface boundary of a unit is important to interpretations of the nature and mode of origin of the unit. Knowledge of the configuration can be inferred from the nature of the rocks forming the unit or by extrapolating downward the attitudes of the contacts where they intersect the surface. Direct measurement of the subsurface configuration of a unit can be made chiefly by seismic reflection and refraction mapping and by gravity and magnetic profiles. The latter two means require supporting information for clear interpretation (particularly gravity), and should be given low priority. The value of mapping the subsurface configuration of a unit is amplified when knowledge of the nature of the surface and its variation is at hand. Therefore, we tentatively recommend that inclusion of active seismic gear not be given high priority for the unmanned lander because such measurements may be better employed at places where the reconnaissance phase has indicated that critical problems exist and because other spacecraft (manned or unmanned rovers) are more suitable to carry such an experiment. Furthermore, seismometers distributed in a surface net (see next paragraphs) by the probes, though intended chiefly for analysis of the deep lunar interior, may provide considerable information on the subsurface configuration of surface units. Consequently, no discrete body geometry measurement is given high priority here.

g. Internal structure. A preliminary understanding of the internal structure (distribution of density and elastic constants) and seismicity of the Moon may be forthcoming from the pre-*Apollo* unmanned exploration of the Moon. The next step in seismic investigations will probably require placement of seismometers at several critical locations and the use of artificially-generated elastic waves to delineate with precision the internal structure. Clearly, if the Moon is internally homogeneous, seismic investigations need not be carried farther; at the other extreme, if the Moon is far from hydrostatic equilibrium, as appears quite possible, careful and extensive seismic work will be necessary to understand the density distributions. The emplacement of simple seismometers at critical locations by unmanned landers presents an optimum opportunity for such seismic investigations. Inclusion of a seismometer on the lander payload should receive high priority.

h. Atmospheric variations. Atmospheric phenomena, if uniform over the Moon's surface, should be measured by a long-term manned lander because, in this case, the measurement does not constitute an area-dependent variable but, more likely, might be a time-dependent one. If, however, gases are escaping continuously from points on the surface, the measurement of atmospheric pressures and composition could fall into the reconnaissance role of the unmanned probes. It could be argued that the places where gas probably is being emitted from the Moon could be determined either by theory (i.e., certain craters, rilles, etc.), by Earth-based observations of activity (Aristarchus, Alphonsus), or by highly sensitive absorption analyses from a lunar orbiter. If this is so, atmospheric measurements would fall more into the category of special problems to be investigated at certain places by manned vehicles, rather than general category of reconnaissance for characterization of the broader aspects of the lunar surface. In the light of these considerations, atmospheric measurements can only be given a relatively moderate priority for stationary unmanned landers.

i. Measurement of properties critical to Orbiter. The properties of the surface materials that are of importance to interpretation of the measurements of the manned lunar orbiter are indicated in Table 2. In the above discussions of each of these physical properties, however, it was concluded that many of them are interrelated, and that knowing the surface lithology and one or two of these physical properties would allow calculation of approximate values of the other variables. Consequently, judgment is required as to whether the unmanned lander should attempt direct measurement of values for each of the potentially important physical properties (probably to the exclusion of other measurements), or whether it should attempt to obtain, within its limited payload, more fundamental information on surface materials from which these properties can be calculated. We strongly recommend the latter approach for the following two reasons:

1. Values of physical properties do not indicate the type of the material that they represent; that is, the physical properties are dependent variables from which a family of particular solutions of the independent variable (the rock material) may be obtained. Consequently, direct measurement of the physical properties of the material would fulfill the probe's role of determination of orbiter properties but would provide rather little information on the two other roles assigned the probe—unit characterization and surface net array. Conversely, emphasis on these latter two roles will provide considerable data from which orbiter properties can be calculated.

2. Measurement at a point on the lunar surface of exact values of certain non-fundamental properties is a dubious procedure. No basis for lateral extrapolation of these values will exist if the nature and origin of the rock material on which the properties are measured is not understood. If, however, emphasis is placed on the nature of the rocks, the lateral variability of the unit can be inferred, and the consequent variation of the orbiter properties

will be indicated. This is equivalent to saying that one should first understand the processes and materials that give rise to values of certain physical properties before exact values of the properties are measured.

j. Conclusions. On the basis of the criteria and discussions given above, the measurements given in Table 4 are considered to be of high or moderate priority for unmanned stationary landers. Within this list, numerical priorities have been assigned, since it is highly probable that an unmanned probe will not be able to carry instruments for all these experiments simultaneously. The priorities are considered to provide the most fundamental and general set of measurements for most of the conceivable geologic situations on the Moon or Earth. The priorities within Table 4 will change, however, if it is found that special circumstances exist or that certain specific problems are critical to the smooth functioning of the *AES* program and are problems which an unmanned probe can investigate. It is possible to anticipate that the priorities of phase analyses, textural examination, volatile compound measurements, atmospheric measurements, and active seismic work may shift in going from general reconnaissance to specific problem investigations. It should be emphasized that each specific problem may require a different set of measurements, and each should be considered as a discrete deviation from the general set given in Table 4. The need for payload flexibility is, thus, indicated.

The next section presents the possible instrumentation with which these measurements can be made. For each measurement, we attempt to select the best experimental method.

3. Lander Measurement Techniques

The following paragraphs outline experimental methods of potential use in carrying out each of the desired measurements given in Table 4. The purpose here is to provide a basis for choosing a final instrument payload assemblage. Many of the measurements in Table 4 can be made by different techniques and, thus, by various instruments. Each technique has particular virtues and inherent limitations that determine its suitability for conducting the measurement on the Moon. An attempt will be made to review each measurement in regard to the most applicable techniques and instrumentation and to assess the relative merit of each; comparisons will be made in terms of the versatility with various geologic cases, completeness of data, precision and accuracy, instrument complexity and reliability, and spacecraft requirements. A summary of all experimental techniques of which we are aware for the measurements of Table 4, together with estimates of the above parameters, is given in Table 5. Discussions follow of the relative value of each technique per measurement.

Table 4. General priority of stationary probe measurements

Priority	Measurement
1	Phase analyses
2	Surface net seismic measurements
3	Mineral textures
4	Surface density
5	Surface fabrics
6	Surface geometry
7	Major element abundances
8	Volatile compounds
9	Radioactive isotope abundances
10	Atmospheric total pressure and composition
11	Active seismic measurements (sources on probe)

a. Phase analysis. Required for solid phase analysis is a means for distinguishing, identifying, and determining the relative abundance of individual mineral or glass phases in a multiphase assemblage. About six methods of analysis can be suggested, of which only three can resolve individual phases of a rock and are well-proven and spacecraft-adaptable techniques: (1) X-ray diffraction, (2) polarizing visible transmission microscopy (petrographic microscope), and (3) reflection optical microscopy or, simply, "hand-specimen petrography." The relative accuracy and precision of these three methods depends primarily on the character of the assemblage being analyzed, in particular, on the grain size. The simplest method of phase identification is hand-specimen petrography (e.g., by a high-resolution vidicon image). For extremely coarse-grained rocks (i.e., $>>$ 1 mm minimum grain size), the nature of the rock can be assessed qualitatively by some form of magnification; but for fine-grained rocks, resolution is so poor that this technique is nearly useless. Transmission optics is likewise largely dependent on coarse grain size for success; however, the petrographic microscope can identify much smaller grains than can a binocular microscope and has the added ability of distinguishing gradational changes in phase composition of a single grain. Both optical methods, however, have the limitation that only known phases can possibly be identified; neither method provides fundamental data from which the nature of an unknown phase can be determined. X-ray diffraction yields quantitative phase determinations independent of grain size, although the sample usually must be finely powdered for proper analysis. X-ray diffraction data are usually interpreted by comparison with the data of known phases; however, X-ray data of unknown crystalline minerals allows recognition of them as such, and may be suggestive of the crystal symmetry and composition of the unknown. In terms of phase composition determination, a spacecraft-adapted diffractometer could provide quantitative data nearly as complete as a standard laboratory instrument. But a spacecraft-adapted microscope cannot provide quality of optical data on phases as could a laboratory microscope (such as optic-angle, optic sign, extinction-angle, birefringence, etc., which measurements are necessary for precise composition determinations). In this compositional sense, then, the diffractometer data are more complete and significant than microscopic data because the diffractometer provides not only phase composition but a good estimate of the bulk elemental composition of the rock. The microscope, however, provides invaluable textural data on the size, shape, and geometrical relations of individual phases and grains of a rock, data which are undeterminable with the diffractometer. Both the petrographic microscope and the X-ray diffractometer require collection and preparation of samples for optimum results, although the diffractometer can be designed for surface deployment. The microscope requires that sample grains or particles be immersed in a suitable transparent medium, a process which is not conducive to deployment operation.

Differential thermal analysis and infrared absorption spectra are useful in particular mineralogical studies, chiefly those involving hydrous phases, but they do not provide data suitable for identification, abundance, and composition determination of the wide range of solid phases in common geological materials.

*b. **Internal structure.*** The objective is to continuously monitor the seismic activity at two or more widely separated *Lunar Survey Probe* landing points for time periods in excess of one month. Seismic sources could be moonquakes or meteorite impacts; in the case of a quiet Moon with only highly infrequent impacts, large artificial source may be considered. Parameters to be measured are:

1. Arrival times of P and S waves
2. Azimuth of approach of seismic waves

Instruments that are capable of monitoring seismic activity include short-period single-axis and multi-axis seismometers. The single-axis instrument, although most rugged and reliable, is the least sensitive and is incapable of detecting long-period surface waves. A three-axis seismometer, on the other hand, will give three mutually perpendicular components of ground motion and can be used to determine azimuth of approach of surface waves.

Delicate long-period seismometers suitable for measuring surface and body-wave dispersions and free oscillations of the Moon are best used on the long-term manned landers. For the surface net of small seismometers, emphasis should be placed on a short period response to body waves.

*c. **Texture.*** Rock texture includes the size, shape, and relative orientation of grains and/or particles that make up a multiphase crystalline or particulate rock. For noncrystalline glassy rocks the degree of vesicularity is required in terms of porosity, vesicle size and shape, and vesicle orientation. The only available method for carrying out these determinations is visible microscopy, using either the polarizing microscope of grain mounts or simply high resolution reflection images. Here again grain size is an important factor; for fine-grained rocks the polarizing microscope is superior, while for coarse-grained rocks, the reflection images are more useful. (There is good reason to believe that extremely coarse-grained rocks will be rare on the Moon.) Partial textural information may be obtainable from other instruments on the spacecraft such as the sample drill, whose penetration rate will be a partial function of grain size and porosity of the rock. For particulate rocks composed of several different particle sizes a stack of sieves of suitable mesh sizes might be adequate for determining the size distribution of particles.

*d. **Surface density.*** The bulk density of surface rock should be determined to an accuracy of ± 0.10 g/cm^3. The only available way that this can be done without disturbing the rock is by using a so-called gamma-gamma backscatter device that effectively determines the linear absorption coefficient of the surface material by measuring the amount of attenuation of a beam of gamma rays. The linear absorption coefficient is a function of the bulk density of the material and the amount of void

Table 5. Possible experimental techniques for stationary probe measurements

Priority	Measurements	Experimental techniques	Space hardware development status	Completeness of data and technique limitations	Precision and accuracy	Additional measurements contribute to or adaptable to	Major incompatibilities with other instruments and/or s/c bus	Accessories or special handling requirements	Time req. for measurement, min	Weight, lb	Power, w
1	Phase analysis	X-ray diffractometer	Prototype	Quant. data, any grain size	Mod–high	Elements, volatiles	Requires high power	Sample prep., or deployment	30	20	45
		Polarizing microscope	Breadboard	Grain size dependent, qualitative	Mod–low	Texture, fabric	None	Sample preparation	5	5	10
		High resolution reflected light images	Prototype	Very qualitative, grain size dep.	Low	Texture, fabric	None	Deployment	5	(3)	(2)
		Differential thermal analyzer	Feasibility	Unable to resolve many individual phases.	Low	Volatiles	Heat generator	Sample preparation	(30)	10	10
		Infra-red spectrometer	Feasibility	Severe sample preparation requirements		None	None	Sample preparation	?	?	?
		Luminescence spectrometer	None	Unproven technique		None	None	Sample preparation	?	?	?
2	Seismic surface net	Seismometer (single-axis)	Flight	Short period and single axis limit depth and direction determining ability	Mod	None	Affected by vibration	Firm mechanical coupling with lunar bedrock	Continuous	28	1
		Seismometer (three-axis)	Prototype	Multi-axis allows azimuth determination	High	None			Continuous	35	1
3	Rock texture	Petrographic microscope	Breadboard	Grain size dependence	Mod–high	Phases, fabric	None	Sample preparation	5	5	10
		High resolution reflected light images	Prototype	Coarse grain rocks only	Mod–high	Fabric	None	Deployment	5	(3)	(2)
		Penetration drill	Breadboard	Very qualitative, ambiguous	Low	Density	Vibration, reaction force against bus	Deployment	<10	(6)	(10)
		Sieves	None	For particulate rocks only	Low	None	Vibration, dust agitation	Sample scooper	(10)	(4)	(5)
5	Rock fabric	Surveillance television	Flight	Color differentials by filters	High	Topography	None	Boom mount for stereo	Continuous (1 sec/frame)	21	400
		Close-up stereo TV		Requires good lighting	High	Texture	View obstruction by bus	Dual lens or boom mount for stereo	Continuous (1 sec/frame)	20	400
6	Surface geometry	Surveillance television	Flight		High	Fabric, texture	None	Color filters	Continuous (1 sec/frame)	21	400
7	Major element analysis	X-ray spectrometer	Prototype	High sensitivity matrix effects; requires powder sample	Mod	None	e/m background	Sample prep. or deployment	30	25	(30)
		Alpha scatterer	Flight	Variable sensitivity poor resolution of K and Cu, iron & nickel	Low	None	Radioactive source	Sample prep. or deployment	180	14	1
		X-ray diffractometer	Prototype	Good data if crystalline; limited if glass	Low–mod	Phases, volatiles	None	Sample prep. or deployment	30	20	45
		Neutron activation	Breadboard	All elements, time-dependent, source problems	Mod	None	Sample becomes intensely radioactive	Sample prep. or deployment	30		
		Gamma-ray spectrometer	Flight	Detects natural radioactives (K^{40}, U, Th) and cosmic ray induced Na, Al, Fe	Low	Radio isotopes	Must be away from bus to minimize bus interference	Requires boom mount	Continuous	18	3
		Petrographic microscope	Breadboard	Requires coarse grain crystalline material	Low	Phases, texture	None	Sample preparation	5	5	10
		Visible emission spectrometer	Feasibility	Critical and complex sample preparation required	?	None	?	Sample preparation	?	?	?
		Mass spectrometer (solids)	Breadboard	No sample preparation required with sputtering ion type	?	Vocatiles, atmosphere	Magnet	Sample preparation	?	(10)	(10)
		Wet chemical (discrete reactor)	Feasibility	Separate reactor device for each element	Low	None ?	?	Sample preparation	?	2 (ea)	1 (ea)
		Neutron inelastic scatterer	Feasibility	Limited to several elements (Fe, Mg, Al), low sensitivity	Low	None	Radiation	Deployment	?	(30)	(30)
		Polarography device	None	Requires electrochemical solutions good only for base metals	Low	None	None	Critical sample prep.		?	?
9	Natural radioisotopes	Gamma-ray spectrometer	Flight	No sample preparation necessary	High	None	Away from bus	Boom mount	Continuous	18	3
		Ionization chamber		Poor resolution	Low	None	None	None	Continuous	3	1
		Mass spectrometer (solids)	Feasibility	Complex sample preparation required	Low	Elements	Magnet	Sample preparation	?	(10)	(10)
		Film dosimeter	None	Low resolution	Low	None	None	None			
		Scintillation dosimeter	None		Low	None	None	None			

(Cont'd)

Table 5. (Cont'd)

Priority	Measurements		Experimental techniques	Space hardware development status	Completeness of data and technique limitations	Precision and accuracy	Additional measurements contribute to or adaptable to	Major incompatibilities with other instruments and/or s/c bus	Accessories or special handling requirements	Time req. for measurement, min	Weight, lb	Power, w
4	Surface density (bulk)		Gamma-gamma backscatter	Breadboard	Simple. Requires deployment, sensitive to surface irregularities	Mod	None	Radiation	Deployment	10	10	3
			Scale (wt of known vol)	None	Crude; requires disrupting surface	Low	None	None	Deployment	10	?	?
10	Atmosphere	Total pressure	Ionization gage	Feasibility	Simple; not mass dependent	High	None	Sensitive to outgassing bus	None	Continuous	(2)	(1)
			Mass spectrometer (gas)	Breadboard	Mass range 12–66	High	Volatiles, elements, atmosphere	Magnet, bus contamination	None	Continuous	6	8
			Bourdon tube	Feasibility	Insensitive to high vacuum	Nil	None	None	None	Continuous	?	?
		Composition and partial pressures	Mass spectrometer (gas)	Breadboard	Mass range 12–50	High	Volatiles	S/C contamination, magnetic		Continuous	6	8
			Gas chromatograph (inorganic)	Prototype	Insensitive to exterior low pressures	Low	Volatiles	S/C contamination	Carrier gas	Continuous	14	15
			Photon absorption	Feasibility	Requires extreme path length. Could utilize moon–earth telemetry signal	Nil(?)	None	None		Continuous		
			Discrete chemical reactors	Feasibility	Insensitive to low concentrations	Low	Volatiles	None		Continuous	2 (ea)	1 (ea)
11	Subsurface Body Configuration		Short-period seismic detector	Prototype	Requires known baseline distance to source	Mod	Seismicity	None	Surface coupling	Continuous	0.5	1
			Explosive charge(s)	Feasibility	Requires emplacement away from s/c	—	None	Shrapnel damage to S/C	Deployment projectiles	?	(1)	(0)
8	Volatile constituents		Multistep heater (DTA)	Feasibility	Simple. Requires some sample preparation and connection to gas analyzer	High	—	Heat dissipation	Sample preparation	30	5	15
			Gas chromatograph (inorganic)	Prototype	Less sensitive to inorganic gases	Low	Atmosphere	None	Sample preparation	60	14	15
			Thermogravimeter	None	No specie resolutions	Low	None	?	Sample preparation	?		
			Mass spectrometer (gas)	Breadboard	Mass range 12–66	High	Atmosphere	None	Sample preparation	Continuous	6	8
			Discrete chemical reactor	Breadboard	Separate reactor for each gas specie limits resolution	Mod	Atmosphere	None	Sample preparation	Continuous	2 (ea)	1 (ea)

space. This technique is simple and reliable but requires deployment of the instrument to the surface and is sensitive to surface irregularities. Another possible method would be to determine the weight of a known volume of material scooped from the surface. This would yield a very crude bulk-density measurement of the material and could be very ambiguous due to disturbance of the sample character during its acquisition.

*e. **Fabric.*** The fabric of a rock is the geometric configuration of both internal textural parts and any pattern in the rock owing to distribution of textures or minerals. Examples are bedding planes in depositional rocks, preferred orientation of vesicles and/or crystals in lava flows, and foliations and lineations in deformed rocks. These features of a rock are defined in many instances by differences in color and reflectivity within the rock and, thus, can be measured in a qualitative manner by visual means. A downlooking TV camera is the only practical means of observing fabric; measurements of size and orientation of fabric elements can be made from the TV images and the appropriate scaling and orientation factors of the camera. An optimum TV system for fabric analysis would include stereo coverage of the surface around the lander at effective distances of 2 to 10 feet; color filters for spectral reflectivity measurements should be provided. The camera system for fabric analysis could also be used for the surface morphology observations by an appropriate lens change or use of a zoom-lens.

*f. **Surface geometry.*** Surface morphology includes both small-scale and gross structural features of the lunar surface within the visual range of the spacecraft. Examples are craters (shapes, wall configuration, depth/diameter ratios, slope angles, etc.), rilles, faults, boulders, and talus piles. Measurements would consist of determining the absolute and relative size and position of features as well as their elevations and slope angles. A survey TV system with stereoscopic and zoom-lens capabilities is required. The present *Surveyor* survey system would be adequate with the following improvements:

1. Increase zoom lens stops to more than the present two.
2. Include more color filters than the present four, to increase spectral resolution.
3. Provide multi-position polarizing filters.
4. Increase height of camera mirrors to more than the present 6 feet (approximately).
5. Increase dual camera or single-camera dual-position baseline distance to more than present 5 ft (approximately) for better stereo-ranging capability.

A survey TV system should have the dual capability of both large-scale surface morphology observations and smaller-scale fabric observations. The system would also contribute to texture determinations and serve to relate texture and fabric to larger scale structural features of the surface.

*g. **Major elements.*** The major rock-forming elements are: Si, O, Al, Na, K, Ca, Fe, Mg, and Ni (in meteorites). The objective is to determine the relative concentration of these elements in lunar rocks. Many methods are available for elemental analysis, of which only a few are capable of detecting and measuring abundances of all the above named elements; these usable methods are X-ray fluorescence spectrometry, alpha-particle scattering, mass spectrometry, and neutron activation.

X-ray spectrometry, using a source harder than Cu K, is sensitive to all the major elements as well as the minor elements of interest such as Mn, Ti, and P. However, it is doubtful that it can detect oxygen very well; in general, its sensitivity increases with atomic number in the range of the rock-forming elements. Alpha-particle scattering, on the other hand, has low sensitivity at high atomic number but increasing sensitivity with decreasing atomic number, and is very sensitive to oxygen and carbon as well as nitrogen and argon. Present alpha-scattering instruments are unable, however, to distinguish K from Ca and Fe from Ni, the ratios of which are important petrologic parameters. Neutron activation, which detects elemental abundances by measuring the energy and intensity spectrum of induced gamma radiation, is capable of analyzing all the major elements as well as some minor elements, although it is severely time-limited due to the relatively short half-life of some of the activated elements and requires an intense source of neutrons; packaging and weight problems are thus severe. Mass spectrometry has particularly high sensitivity for elemental analysis of solids. Current solid-source mass spectrometer designs (Herzog, et. al., GCA Corporation, TR 65-7-N, 1965) utilize a sputtering ion source which eliminates most of the problems encountered with earlier spark-discharge sources and is particularly useful for non-destructive surface analyses. Furthermore, the sputter-ion mass spectrometer can be used for the analysis of both solids and gases. The most widely used technique for elemental analysis is that of visible emission spectroscopy where the sample is evaporated in a spark-discharge and the characteristic emission lines of the elements present are measured with a spectrometer. This technique is extremely sensitive to all major elements, but is not currently being developed for space application because of extreme complexity.

X-ray diffraction can give partial elemental data indirectly by measuring crystalline phase abundance and by fluorescence of X-rays in the diffraction sample of major elements of $Z <$ Source Z; where Cu is used, Fe, Cu, K, Al, and Si may be assessed. Gamma-ray spectrometry is sensitive only to natural-radioactive K^{40}, Th, and U, as well as cosmic-ray activated Al^{28}, Na^{24}, and Fe^{56}; thus it would be suitable only for measuring K, Na, Al, and Fe in surface-exposed rocks. Neutron inelastic scattering is sensitive only to Fe, Mg, and Al, and thus would be of limited utility except as an adjunct to the neutron activation method.

h. Volatile constituents. Volatiles can exist in a rock in two forms: (1) as condensed or adsorbed components filling interstices or adhering to grain surfaces, respectively, and (2) as chemically combined components such as the water molecule or hydroxyl ion. If as condensed components they are in solid form (e.g., ice) they might be detectable as solid phases with an X-ray diffractometer; however, it is very unlikely that they would survive sample preparation without evaporating. As chemically combined components of hydrous minerals they would also be determinable from solid phase analysis with a diffractometer or petrographic microscope. However, if the volatiles occur as trapped gases in vesicles or as adsorbed molecules they must be liberated from the rock by crushing and/or heating the rock and channeling the evolved gases into a gas analyzer.

Of particular petrologic significance is the temperature at which gases are evolved from rocks upon heating. The ideal way to liberate the gases, then, is by use of a differential thermal analyzer (DTA) which heats the rock sample slowly, or in steps, to a maximum temperature near fusion. The composition and concentration of effluent gases are then measured by a suitable gas detection device and correlated with the temperature at which they were evolved.

Three different types of instruments, all of which are currently being developed for space applications, are available for gas analysis: mass spectrometer, gas chromatograph, and discrete reactors. The mass spectrometer is extremely sensitive to small concentrations of gas and has excellent resolving power up through mass 66 (SO_2). However, for H_2O detection, particular care must be exercised in the instrument design to avoid excessive absorption. A sputtering ion type of solid-source mass spectrometer can be used for both solid and gas analysis; thus, both major elements and volatiles can be analyzed with the same instrument.

The gas chromatograph can be adapted for inorganic gas analysis and is quite sensitive to trace amounts of most gases but requires a large flow of carrier gas. The gas chromatograph is not suitable for analysis of low concentrations of H_2O because of irreversible absorption in the chromatograph apparatus.

The simplest type of gas analyzers are the so-called *discrete reactors* or *simple composition* devices which are sensitive (by design) to only a single specie of gas and, thus, can determine *partial* pressures. The most successful of these devices is designed for H_2O determinations and utilizes an aluminum-aluminum oxide-gold capacitance bridge or P_2O_5 resistor whose RF impedance and dc resistance, respectively, are functions of water vapor pressures; these devices have concentration sensitivity ranges of approximately 4 orders of magnitude. Similar devices can be used for detection of oxygen, SO_2, and other gases.

i. Natural radioactive isotopes. The objective here is to measure the amount of natural gamma activity from radioactive isotopes of K, U, and Th in lunar rocks. A gamma-ray spectrometer utilizing a scintillating detector and pulse-height analyzer can resolve the individual gamma contribution of each of the three natural radioactive isotopes and, most important, separate out the contribution from cosmic-ray induced radioactive isotopes of Al, Na, and Fe. If a lunar sample could be obtained from several meters below the lunar surface (i.e., unexposed to cosmic rays) a simple scintillation counter without pulse-height analysis would yield an estimate of the bulk natural radioactivity of the rock. The alpha-scattering device has fairly high sensitivity to the sum of U and Th and would probably yield as good, if not a better, measure of these than would the gamma ray spectrometer.

j. Atmosphere. Both total pressure and composition (and, thus, partial pressures) of the lunar atmosphere are desired. For total pressure measurement the simplest instrument is an ionization gage; however, it is not suited for partial pressure analysis and would have questionable accuracy at pressures expected on the Moon ($< 10^{-13}$ torr). A bourdon-tube type of gage is even more insensitive to these low pressures. Again, the gas chromatograph and discrete reactors are likewise unsuited for extremely low-concentration analysis. The only satisfactory instrument for lunar atmosphere measurement is a mass spectrometer, which can provide the required total and partial pressures and, most important, is sensitive in the 10^{-13} to 10^{-15} torr range.

k. Subsurface body configuration. Active seismic measurements provide the best means for making this measurement from a point; they consist of inducing seismic waves in the lunar surface by explosive charges and measuring the travel time and wave amplitude at a known distance from the detonation point. The simplest instrumentation would consist of a single detector emplaced in the lunar surface beneath the probe, and grenade-type explosive charges that are propelled radially at known distances from the probe and ignited on impact or by a pulse through a trailing wire from the probe. Experimental results (Kovach and Press, JPL, TR 32-328, 1962) indicate that a 1-lb explosive charge will be adequate for a 2000-ft seismic-profile. This assumes a low background noise level on the Moon. For deeper depth penetration, heavier charges and longer profiles will be required, possibly through the use of a roving vehicle. The short period seismometer suggested for the surface-net internal-structure measurement might form a suitable detector for this experiment, although only a single-axis is needed in this case.

4. Recommended Instrument Assemblages

Based on the comparisons presented above, three instrument assemblages are recommended for the priority measurements. The instruments in each assemblage are chosen on the basis of meeting the following three sets of conditions:

Assemblage A.	Assemblage that comprises best instrument for each measurement, yielding most complete data for each measurement; no particular weight or power limitations
Assemblage B.	Lightweight assemblage, yielding minimum required data for each measurement; no particular power limitations
Assemblage C.	Low power assemblage, yielding subminimal data for each measurement; no particular weight limitation

The instrument assemblages are listed in columns A, B, and C of Table 6.

5. Rover Measurements

The chief roles given the unmanned rover in the previous section are ones in which the nature of lateral variations on the Moon are sought. The existence and location of discontinuities or rapidly-changing properties will be indicated by orbiter, but the actual surface and subsurface lithology and structure which express these changes may largely remain uncertain. The measurements that a rover should make would, thus, be of properties which cannot be measured by orbiter or where orbiter data is of insufficient resolution for accurate knowledge of variations.

Two rover capabilities form limits to its mode of scientific operation. Case 1 would be that of a characterization payload similar to that of the stationary probe. Here, a sequence of *digital* points would be made across a zone of changing properties. Because the rover lifetime and power capabilities are not great, one might assume the points will be widely spaced. Thus, we would know rather precisely the nature of the Moon at these points, but the uniformity and changes between points would not be certain. The opposite case is given by a rover with continuous measurements of certain types that effectively form a sequence of infinitely-closely spaced points along the traverse. Measurements in the latter case would largely be qualitative but would indicate any local variations of properties that might not be detected by the more widely-spaced point measurements of Case 1.

In suggesting a priority of measurements for rover, we lean toward the philosophy of Case 1, above. This is because the kinds of quasi-continuous measurements of which we can conceive (topography, reflectivity, gamma-ray spectra, gamma-gamma density, etc.) are either non-unique in defining what surface properties are changing, or because similar data will already have been acquired by orbiter. Further analyses of structural and stratigraphic relations on Earth are chiefly by visual, deductive methods by geologists *in situ*. Consequently, we can estimate that similar problems to which rover would be devoted would be based on topographic and reflectivity variations obtained by orbiter. The orbiter stereophotography should have resolution approaching a few cm, and full description of the larger-scale surface geometry will already be in-hand. Thus, the rover should be used for the ensuing steps that a field geologist or geophysicist would employ—those of defining what causes the topographic and reflectivity variations.

On these bases, certain measurements are proposed below. It should be mentioned first that non-stereo panoramic visible images of the terrain about the spacecraft are necessary for local navigation and flexibility to make measurements at the locally most interesting spots.

1. *High resolution visible imaging.* Monoscopic, high resolution (0.1 mm), color images of the near-vicinity of the vehicle can provide a broad context on the fine-scale surface geometry which may reflect either changing material or changing process of formation. Secondly, such observations may suggest the nature of the material in the manner of hand-lens identification.

2. *Active seismic studies.* A seismic line can be laid out by the rover at pre-established points. Data on the subsurface configuration of the zone in question can be obtained by this means. The rover could lay out charges at certain intervals which could be detonated by different radio frequencies. At the end of the traverse, a geophone could be emplaced and the charges detonated in sequence. The arrival times of elastic waves could then be recorded.

3. *Material characterization experiment.* The lithologic character of the surface material should be assessed at places where either the orbiter or rover visual descriptions indicate significant surface changes. The experiment should involve rapid analysis and be deployable from the vehicle without requiring sample preparation. An X-ray fluorescence device appears to us to give the best possibility for short analysis time, *in-situ* analysis, and an abundance of significant data of the range of materials analysis techniques available.

4. *Continuous measurement devices.* Certain measurements are amenable to nearly-continuous analysis, possibly during rover movement or else during exceedingly short stop-times. These could be significant in detecting local variations in properties or in providing precision in determination of the rate of change of properties over a longer distance. They are not specific, however, as to the fundamental changes that occur. They are gamma-ray spectroscopy, gamma-backscatter surface-density measurement, and some form of static or dynamic surface-hardness testing device.

Table 7 summarizes these priorities and gives appropriate instrumentation.

6. Value of *Apollo* Site Certification Measurements to *AES* Exploration

a. Introduction. The chief purpose of many of the instruments that are being developed for inclusion in the payloads of *Surveyor I, Surveyor II,* and *Apollo* lunar survey probes (hard-lander, survivable capsule) is to make measurements suitable for *Apollo* landing-site certification. The instruments and measurements are intended to establish the nature of such surface parameters as slope angles, size of protuberances, and surface hardness. If these same instruments and measurements were subsequently used in the *AES* program, how useful would they be? How much information could be obtained with them that would apply to the types of measurements recommended for the *AES* program (Section III B-2 above)? In the following discussion, we first list the instruments and measurements in question and the functions for which they are designed; then an evaluation of their individual usefulness to *AES* science is presented; finally, there is a general summary of the overall utility of site certification measurements in a scientific exploration program.

b. Site certification measurements and instruments. Measurements for site certification fall into two general categories: (1) those that determine the nature of the topography on a scale of several feet, and (2) those that measure the mechanical bearing strength of the lunar soil. These can be broken down to the more specific parameters of slope angle, height of relief features, static bearing strength, cohesiveness, and depth to bedrock. Examination of these parameters will be achieved not only by direct instrumentation but by interpretation of the behavior of spacecraft components (i.e., landing pads) upon touchdown. The desired parameters and the methods and instrumentation being considered for their measurement and listed in Table 8 for the three spacecraft types (*Surveyor I, Surveyor II,* and *Apollo* survivable capsule) from which site certification data will be obtained.

c. Scientific value of site certification measurements. The only measurements listed in Table 8 that are of direct scientific interest are topography and depth-to-bedrock; the rest are of only indirect interest and to varying degrees. The scientific value of each measurement can be estimated as follows:

1. *Topography.* The topographic configuration of the surface is of prime scientific interest because topography is a record of surface processes that have

Table 6. Recommended scientific payloads for stationary probes

Priority	Measurement	Unit characterization and general reconnaissance missions											Surface net mission D Seismic station establishment			Orbiter support mission E		
		A Best instrument for each measurement: most complete data				B Lightweight assemblage: minimal data for each measurement			C Low power assemblage: subminimal data for each measurement									
			Wt, lb	Vol, in.^{3}	Power, w		Wt, lb	Vol, in.^{3}		Wt, lb	Vol, in.^{3}	Power, w		Wt, lb	Vol, in.^{3}		Wt, lb	Vol, in.^{3}
1	Phase analyses	X-ray diffractometer	20	1000	60	X-ray diffractometer	20	1000	Petrographic microscope	5	500	10	—			X-ray diffractometer	20	1000
2	Internal structure	3-axis seismometer	35	800	1	1-axis seismometer	28	100	3-axis seismometer	35	800	1	3-axis seismometer	35	800	—		
3	Textures	Petrographic microscope	5	500	10	Lightweight survey television on adjustable boom, with multiple lenses and vertical downward looking capability	25	700	(Petrographic microscope)				—			Petrographic microscope	5	500
5	Fabric	Survey television	21	1000	400				Survey television on adjustable boom	10	300	100	Single lens television on fixed boom	10	150	Survey television on adjustable boom	20	300
6	Surface geometry	Closeup television	21	1000	400													
4	Density	Gamma-gamma back-scatterer	10	200	3	Gamma-gamma backscatter	10	200	Gamma-gamma backscatterer	10	200	3	Gamma-gamma backscatter	10	200	Gamma-gamma backscatter	10	200
7	Elemental abundances	X-ray spectrometer	25	800	50	Alpha-scatterer	14	300	Alpha scatterer	14	300	1	—			—		
8	Volatile compounds	DTA-mass spectrometer	5	400	23	DTA-simple reactor (for H_2O only)	3	100	DTA-simple reactor (for H_2O only)	3	100	16	—			DTA-mass spectrometer	5	400
9	Radioisotopes	Gamma ray spectrometer	18	250	3	Scintillator (2-channel discrim.)	5	100	Scintillator (2-channel discrim.)	5	100	2	—			—		
10	Atmosphere	Mass spectrometer	6	300	8	Ion gage	2	100	Ion gage	2	100	1	—			—		
11	Subsurface configuration	Geophone and charges	3	50	2	Geophone and charges	3	50	Geophone and charges	3	50	1	—					
	Totals		189	6300			110	2650		87	2450		—	55	1150		60	2400

Table 7. Priority of unmanned *Rover* measurements

Priority		Instrument	Weight, lb	Power, w	Cumulative wt, lb
No.	Measurement				
1	Monoscopic, panoramic, visible images of vicinity of vehicle. (Resolution of, say, 1:100)	Television	14[a]	150	14
2	High resolution (0.1 mm) imaging of area within a few meters of vehicle	Television	6[b]	—	20
3	Subsurface structure	Active seismic gear	20	1	40
4	Rapid in situ material: analysis at points over rover traverse	X-ray fluorescence	20	25	60
5	Surface density	Gamma-gamma backscatter	10	10	70
6	Radioisotope content	Gamma-ray spectrometer	18	3	88

[a] Approximate weight of existing *Rover* system without large boom or power source.

[b] Discrete camera to time-share with panoramic camera. High-resolution lens attachment for pan camera would require less weight, but would be less reliable.

shaped the surface. An imaging system such as that designed for measuring topography would also provide information on subsurface rock structure, rock fabric and, if the resolution is great enough, on surface texture. A stereoscopic imaging system would be superior to a monoscopic system in terms of depth-resolution and close-up textural analysis; however, a monoscopic system is satisfactory so long as it can distinguish a wide range of color and albedo. A valuable addition to the imaging system of *Surveyor* would be elevation of the sensor to 40 or 50 ft above the surface, permitting much wider surface coverage in an area of low relief.

2. *Static bearing strength.* This measurement would be of some value in determining surface density if it can be shown that the static bearing strength of a surface is a function of bulk density of surface material. The bearing strength might also give useful information on the degree of possible vacuum welding, solar-ion sputter welding, and the degree of vesicularity of volcanic bedrock.

3. *Shear strength.* If the lunar surface layer is homogeneous in depth and lateral extent, the measurement of shear strength may have limited utility in interpreting natural seismic waves and/or induced waves from explosive charges. Shear strength is related to shear modulus, which in turn is a fundamental factor in controlling elastic wave propagation.

Table 8. Methods of measurement being developed for *Apollo* site certification which could be utilized on an *AES* probe

Site certification measurement	By *Surveyor I* spacecraft	By *Surveyor II* spacecraft	By *Apollo* survivable capsule
Topography	Stereo TV	Stereo TV, on extendable 40-ft mast	Stereo TV mono TV fascimile
Static bearing strength	Surface sampler		Flat plate penetrometer
Soil shear strength	1. Landing-pad depression 2. Landing-pad skid marks	Sample drill	Shear vane
Dynamic bearing strength	1. Landing-pad impact dynamics 2. Surface sampler	Accelerometer balls	Push-rod penetrometer Thumper plate
Depth to bedrock	Seismometer (if meteor impact produces seismic wave)	Seismometer mortar charges	Seismic sensor mortar charge
Reaction of soil to retro blast (cohesiveness)	Television viewing of vernier rocket cratering effect		Model rocket engine

4. *Dynamic bearing strength.* The accelerometer balls that are being developed for dynamic bearing strength could be modified to carry explosive charges and, thus, could be used for an active seismic experiment. The accelerometers launched in shot-gun fashion would give an idea of the heterogeneity of the surface rock units surrounding the spacecraft, and thus, would give some indication of the subsurface variability of units which otherwise appear uniform. The push-rod type of penetrometer would have little scientific value other than to give a rough approximation of surface rock texture at a single point.
5. *Depth to bedrock.* Determining the depth to bedrock and, thus, the thickness of an overlying surface layer is not only of primary scientific significance but, also, the active seismic method for achieving it is capable of considerably more utility (see Table 3); in the case of an aseismic Moon, the explosive charges may provide the only means of studying subsurface rock structure and internal zoning of the Moon.
6. *Cohesiveness.* By observing the behavior of lunar soil under the blast from a (model) rock engine one may gain some knowledge on the cohesiveness of lunar soil, but the scientific significance of cohesiveness is small unless the mode of formation of the soil is known. The measurement might suggest limits to the extent of vacuum welding or crusting that has occurred on the outer surface of the Moon.

d. Summary of scientific utility of site certification measurements. The only instruments for site certification that will be of direct value to *AES* science are: (1) the visual imaging systems, either stereoscopic or monoscopic, and preferably on a high-boom mount; and (2) the active seismic apparatus consisting of seismometer and explosive charges. These two systems are priority items for *AES* exploration, as discussed in Section III B, above. The remaining measurements in the site certification category will have only incidental utility and cannot be considered as important for *AES* exploration.

C. *Probe Requirements*

1. Introduction

The roles of unmanned probes in an integrated lunar exploration program were presented in Section III A, and the priority of measurements and instruments for a stationary lander and a mobile vehicle were given in Section III B. This section discusses the relative suitability of stationary payload delivery systems (hard- vs soft-lander or *Ranger* vs *Surveyor*) and the relative value of partial payloads of optimum instruments vs complete payloads of less definitive instruments for the measurements of Table 4. Also contained here are considerations of the threshold value of an unmanned rover capability and the change of value of the rover with increasing payload, lifetime, and range in order to accomplish the goals and measurements given above for rover. Lastly, other general requirements for probe operations are presented.

2. Stationary Payload Delivery System

Two types of landers can be considered:

1. *Soft-landers.* With either attached and/or deployable instruments, or a demountable rover vehicle
2. *Hard-lander.* With survival capsule containing instrument assemblage landing at vertical velocity ≤ 200 fps

The relative suitability of these two can be judged by the ability of each to carry the payload given in Table 6 for stationary measurements or by non-payload considerations. Taking the latter first and assuming that both vehicle types have equal payload and surface orientation capabilities, we can compare the following factors:

Factor	*Surveyor*	*Ranger*
Number of vehicles per orbiter	4	20 (for 13-in. ID capsule)
Cost/vehicle landed	6.6 X	X
Terrain limitations to successful landing:		
Local slope	15 deg	no limit
Differential rigid protuberance	10 cm	no limit
Surface strength	50 psi	4000 psi

The number of useful hard-landers that can be placed in an orbiter is unknown to us. The volume of a 13-in. capsule is virtually insufficient for a payload as will be shown later. As the capsule diameter is increased, the number of hard-landers per orbiter will decrease. Since the capsule volume is proportional to a factor of about $d^3/2$, an increase in capsule volume of 6 X would reduce the number of probes by an order of magnitude if the sum of capsule diameters were the only limiting factor.

The point is simply that it cannot be presumed there can be a large number of *useful* hard-landers per orbiter compared with the number of soft-landers.

The terrain limitation factor is highly significant. A rough terrain may not allow successful landing of the existing *Surveyor*-type soft-landers at all points on the Moon, owing to slopes and bumps. The fact that the hard-lander capsule can be placed at all locations regardless of topographic problems makes the capsule seem quite superior to the soft-lander for both the reconnaissance and surface net roles. The values of the two delivery systems, however, are reversed when the bearing strength of the surface is considered for these roles. The soft-lander can be supported by a very soft surface, but the capsule will probably lie entirely above surface after impact only if a hardrock (> 4000 psi) surface exists on the Moon. If a soft layer of thickness of a meter or more exists, the capsule may well be buried. This situation provides certain difficulties for the surface reconnaissance experiments of Table 6; although a seismometer could conceivably continue to function, communications would probably be hindered. Consequently, without extensive prior knowledge of the lunar surface terrain, a soft-lander system seems to provide a greater probability of scientific success.

Each of the stationary lander payloads of Table 6, above, could conceivably be flown in either the soft-lander or the capsule. The shock created by the capsule impact seems intuitively minor, since delicate items such as vidicon tubes have been designed to withstand such impacts.

The payload capacity of the two delivery systems further discriminates the relative suitability of the two delivery systems. Table 9 compares the weights and volumes of the payloads given in Table 6 with weight and volume capacities currently anticipated for probes ejected from lunar orbiters. The scientific instruments must, of course, be provided with power sources, telemetry, and structural support; we have been advised that an appropriate weight ratio of scientific instrumentation to supporting equipment is 1:1.

It can be seen that the capsule is weight limited for all payloads except for the surface net (i.e., seismological) experiment; however, even here, the existing capsule volume is insufficient for a three-axis seismometer. Either the volume of the capsule could be increased or a single-axis seismometer could be employed. The latter would fit in the existing capsule; the mission would thus be identical to that of *Ranger 3, 4,* and 5. The value of a capsule devoted entirely to delivery of single-axis seismometers is questionable, particularly when soft-landing probes will also be deployed concurrently for emplacement of more sophisticated seismometers in conjunction with characterization experiments.

Table 9 shows that the soft-lander can carry all but the best instrument payload. The Table further compares the weights of a minimum weight payload (which contains the lightest, but not necessarily most capable, instrument for each measurement of Table 4) with the weight of a payload which carries the best instruments for the six highest priority measurements of Table 4. The soft-lander can carry either one, and we strongly recommend that the partial payload is of greater value in unit characterization than the minimum weight payload. The reason is that the high priority scale of Table 4 is nonlinear, and the first six measurements are more important than the others.

In summary, the following conclusions can be drawn concerning the capabilities of the capsule and soft-landing delivery systems.

1. *Soft-lander.* This system can deliver a partial payload of the recommended measurements of Column A, Table 6. It can also deliver a complete minimum weight payload (Column B, Table 6) although this payload should be of lower priority

Table 9. Comparison of payload requirements and availabilities for the soft-lander and capsule

Payload type	Total instrument payload weight, lb	Scientific instrument weight, lb	Scientific instrument volume, in.^{3}
Best instrument payload[a]	378	189	6300
Minimum weight payload[a]	220	110	2650
Partial best payload[b]	242	112	4500
Surface net payload[c]	90	45	950
Soft-lander[d]	250	125	?
Capsule[d]	125	62	600

[a] Columns A and B, Table 6; combined unit characterization-seismometer rates.

[b] Column A, Table 6; measurements 1 through 6.

[c] Column D, Table 6; surface net seismometer only.

[d] From L. Nicholson, MSC, Houston, personal communication.

than that above. If the lunar surface is not largely bedrock, the soft-lander appears to provide a higher probability of success in instrument delivery. The soft-lander will be required, also, for delivery of roving vehicles.

2. *Capsule.* This system can deliver a modified version of surface-net seismic experiments at the current capsule volume. If the volume is increased, larger payloads are possible but at the expense of the number of probes per orbiter.

3. Rover System

The unmanned roving vehicle concept for the site certification program is not completely defined; it has been suggested, however, to have a 5 to 10 km operational range, a total vehicle weight of around 100 lb, and measurements consisting of a vidicon imaging system with limited stereo capability and certain vehicular parameters such as tractability and depth of tire tracks. When the capability of this vehicle is considered relative to the measurements suggested for *Rover* in Table 7 and when the data return from the 100-lb rover is compared with the stereo imagery which will have been obtained by orbiter before a rover is deployed, there seems to be little need for such a vehicle in an integrated exploration program.

It was established in Section III A that rover plays an important role in the reconnaissance phase of lunar exploration. A roving vehicle which is improved sufficiently over the present concept to surpass a utility threshold should have chiefly an increased scientific payload. A range of 10 km would be entirely satisfactory for many traverses for which the vehicle would be employed. It is suggested that the threshold payload consists of the first three measurements of Table 7—panoramic imaging, high-resolution imaging, and active seismic apparatus. The total weight of this minimum payload is about 40 lb, an increase of 24 lb over that of the site certification rover; the weight of needed supporting apparatus is not included in that Figure. The total weight of scientific instruments in the optimum payload for rover is 88 lb.

4. Probe Operational Requirements

Regardless of the mode of delivery of the instrument assemblage, certain operational requirements must be met by the probe to ensure the integrity and significance of the mission results. These requirements fall into the categories of landing accuracy, landing position determination, instrument deployment, functional lifetime, and special constraints. The exact limits of each of these must be established for each type of probe mission and instrument assemblage. Some generalities can be made.

*a. **Landing accuracy.*** The roles of the probes do not call for great accuracy in surface placement. The characterization of representative parts of surface units by stationary probes infers that almost any point over a substantial area, probably kilometers wide, would be satisfactory. Conversely, tight landing accuracy requirements (say 100 meters, or less) would not be in consonance with the point character of probe measurements. The accuracy of landing of surface net package might be more important in certain cases where proximity to certain features is desired. In this case, 1/2 km should be satisfactory. The rover should be landed to an accuracy within 10% of its total range.

*b. **Landing position determination.*** For unit characterization and emplacement of a net of surface seismic stations the landing accuracy is not as critical as knowledge of the exact position of the station after landing; thus, if the subsequent position can be determined accurately following landing, the initial landing accuracy can be relatively low. Position location is of first-order importance for most missions because the results of all measurements taken at a point will have maximum significance only in relation to other known lunar features surrounding the point.

*c. **Deployment of instruments.*** A large number of the instruments recommended in Table 3 require some sort of deployment after landing; this consists of either (1) bringing the instrument sensor into contact with, or proximity to the lunar surface, or (2) moving the sensor either high above the surface or away from close proximity to the spacecraft or its impact point. Other similar operations are ejection of the mortar charges for an active seismic experiment and demounting a rover vehicle. Operations such as these require that the spacecraft be designed as a dynamic device capable of complex manipulations as well as passive sensing.

*d. **Probe lifetime.*** The functional lifetime requirement of the probe will depend primarily on the minimum total-time necessary for making all required measurements of a given mission. For the unit-characterization and orbiter-support missions, the minimum times are estimated to be 100 and 50 hr, respectively. These times take into consideration the sequential sharing of power supply and telemetry system by each instrument and the limited rate at which power can be supplied to any single instrument. Additional operating time may be required if measurements of time-dependent lunar parameters are to be made; examples are the effects of Sun-angle on surface properties and shadow-progression studies of topographic features. For these, the maximum lifetime would be the duration of a lunation. For a seismic station (surface net mission) the lifetime should be longer than a lunation.