is attracted by a 500-gauss magnet, that is, magnetite, meteoritic nickel-iron, or free iron. (ii) An addition of 1 percent (by volume) of free iron to a basic terrestrial rock represents an upper limit for the lunar results, by comparison to laboratory studies. (iii) Surveyor V magnet results are most similar to those obtained in laboratory impact studies with 37- to 50-μ powdered plateau basalt with no addition of free iron.

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Note

1. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract No. NAS 7-100, sponsored by NASA.

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Chemical Analysis of the Moon at the Surveyor V Landing Site

Abstract. *The chemical composition of the lunar surface material at a maria landing site has been determined by the alpha-scattering technique. Oxygen, silicon, and aluminum have been identified in the preliminary evaluation of the data. The general chemical composition is similar to that of a silicate of a basaltic type.*

A remarkable amount of information about the moon has been obtained by earth-based measurements. Together with theoretical arguments, these provide clues as to the origin and history of this earth satellite. In the last decade, such earth-based observations have been supplemented by results from the United States and Russian space programs, which have provided high-resolution photographs, data on the physical properties of the lunar surface, and radiation measurements.

Some of the basic questions about the moon, however, can best be answered by a knowledge of the chemical composition of lunar material; until now, observations and measurements have provided only indirect information about this important property. The alpha-scattering experiment of the NASA Surveyor Program is designed to measure directly the abundances of the major elements of the lunar surface. We now report preliminary results of such an experiment at the Surveyor V landing site in Mare Tranquillitatis (23°E, 1°N) on 11 and 12 September 1967.

The α-scattering method of chemical analysis, the instrument used on the Surveyor mission, and the nominal mission operation have been described (*1*, *2*). This technique is especially suitable for instrumented missions in space because of compactness and relative simplicity of operation. It involves the measurement of the energy spectra of α-particles scattered backward from the atomic nuclei of the sample, and of protons obtained from the nuclear reactions of α-particles with some of the lighter elements. These spectra contain quantitative information on all major elements in the sample except hydrogen, helium, and lithium. The method can readily distinguish among the lighter elements, but the atomic weight of heavier constituents can only be approximated.

The alpha-scattering instrument consists of a sensor head, which is deployed directly to the lunar surface, and a digital electronics package located in a compartment on the spacecraft. A collimated stream of alpha particles from approximately 100 mc of curium-242 strikes the sample through an opening (10 cm in diameter) in the bottom of the sensor head. Semiconductor detectors and pulse-height analysis electronics are used to obtain the energy spectra of the scattered alpha particles and of the protons from the lunar surface. Analyses of rocks performed with instruments of the type used on Surveyor V have given results on the major constituents with an accuracy and sensitivity of about 1 atomic percent (*2*).

In the Surveyor V soft-landing mission to the moon (*3*), the sequence of operations of the α-scattering instrument included three distinct stages. In the first stage, the instrument, in its stowed position on the spacecraft, obtained data on a sample of known composition. The first operation of this type was conducted for 1 hour during transit to the moon. The data showed that the instrument had survived the launching, and that radiation-background rates would probably be low enough for useful measurements on the moon. Two hours after landing, the instrument was again turned on by command from the earth; engineering data, including voltages and temperatures, were received and found to be normal. Spectra of the known sample were taken again for about 1 hour, and they agreed very well with spectra obtained before launch.

The sensor head was then released to the background position, suspended about 0.5 m above the lunar surface. During this second stage of operation, the sensor head was far enough from the lunar surface to respond primarily to cosmic rays, solar protons, and possible surface radioactivity. Approximately 3 hours of background spectra were obtained.

The instrument was lowered from the background position to the lunar surface (stage 3) at 15:36 GMT on 11 September 1967. About 20 minutes later, the first spectra from a lunar sample were received at the control center at the Jet Propulsion Laboratory in Pasadena, California, from a tracking station in Robledo, Spain. Television pictures, obtained some time later, confirmed that the instrument had come to rest in a proper manner on the lunar surface. Data were received for a total of 17 hours during the next 2 days.

On 13 September, three liquid-propellant rocket engines (verniers) near the

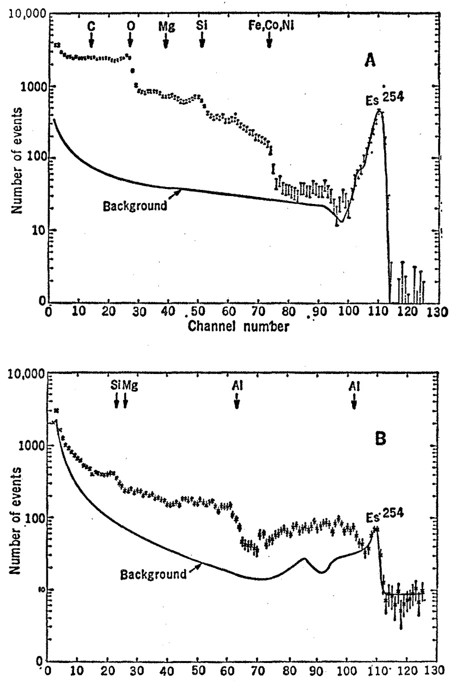

Fig. 1. Spectra of scattered α-particles (A) and protons from (α,p) reactions (B) obtained in 900 minutes of operation of the α-scattering instrument on the moon. The positions of prominent features in some of the elemental spectra are indicated by arrows with chemical symbols.

legs of the Surveyor spacecraft were fired. Pictures taken after this test showed that the sensor head had moved about 10 cm downslope from the spacecraft. When the instrument was again turned on, it was found to be functioning perfectly, and operations were begun at the new lunar surface position.

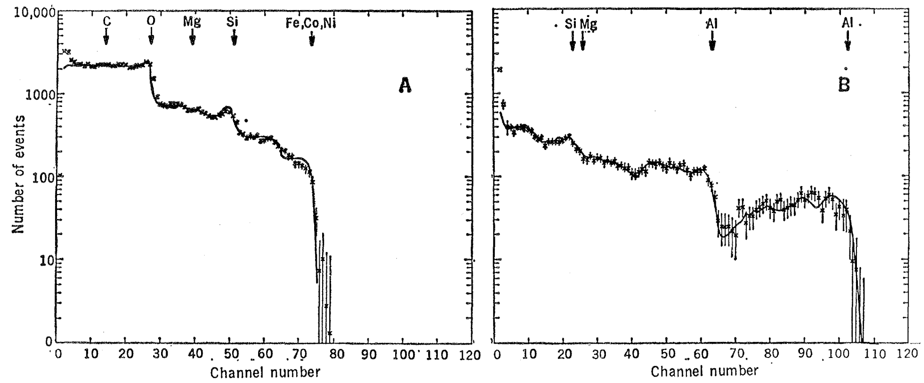

Fig. 2. Least-squares computer fit of the observed lunar data (after subtraction of the observed background, increased in *A* by 12 events per channel for possible contribution by elements heavier than Ni). A library of eight elements (see text), constructed from measurements made on the same instrument before the mission, was used. The positions of prominent features in some of the elemental spectra are indicated by arrows. (A) Alpha mode; (B) proton mode.

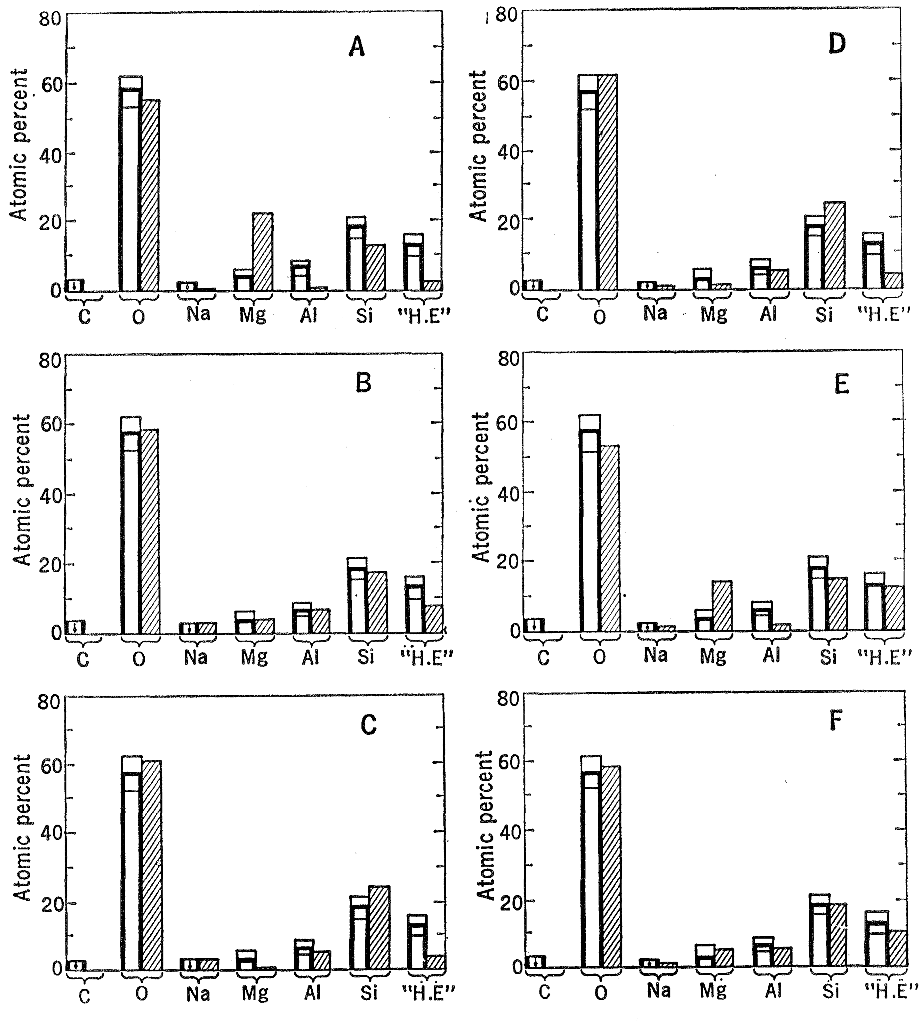

Fig. 3. Comparison of the observed chemical composition of the lunar sample (open bars) with the average composition of selected materials (hatched bars): (A) dunites; (B) basalts; (C) granites; (D) tektite (Indo-Malayan body); (E) low iron chondritic meteorites; (F) basaltic achondrite meteorites (*4*). *H.E.*, elements heavier than silicon.

By the end of the first lunar day, additional data for approximately 65 hours had been obtained. The preliminary results given here are based only on data obtained before the firing of the vernier engines, and thus they apply to the first lunar sample examined.

During these measurements, the instrument operated over a temperature range of +52° to −56°C. All data received were of high quality, except at the lowest temperatures (below the planned operating range). The energy resolution of the instrument and quality of the α-sources, as determined by calibration during the mission, are consistent with data obtained before launch. The ten semiconductor detectors in the instrument functioned properly throughout the first lunar day.

At this date, only part of the data obtained during the mission is available. Moreover, even this has been processed by techniques designed primarily for monitoring instrument behavior during actual mission operations. Thus, the present results relate to a limited number of elements and must be assigned larger errors than will be given at a later stage of analysis. They appear to be firm enough and significant enough to warrant publication at this time.

The observed backscattered α-spectrum and the spectrum of protons from (α,p) reactions from 900 minutes of measurement on the first lunar sample are presented in Fig. 1, A and B. The ordinate in each case is the number of events per channel of the 128-channel analyzer, plotted as a function of the channel number (energy). We have indicated the statistical errors, together with a smoothed version of the background measured while the instrument was suspended over the lunar surface. For most of the α-spectrum, the signal from the α-particles scattered from the lunar surface is an order of magnitude higher than the background. The situation is less desirable, although adequate, in the proton mode. The peaks at around channel 110 in the two spectra are due to the 6.4-Mev α-particles of einsteinium-254 (Es^{254}) placed near the detectors as an energy marker.

Qualitative inspection of the α-spectrum (Fig. 1A) shows distinct break points at energies (indicated by arrows) corresponding to maximum energy scattering from nuclei of mass 16 (oxygen), mass 28 (silicon), and approximately mass 58 (iron, cobalt, and nickel). Moreover, the low response

Table 1. Chemical composition of lunar surface at Surveyor V site.

Element	Atomic percent*
Carbon	< 3 ±
Oxygen	58 ± 5
Sodium	< 2
Magnesium	3 ± 3
Aluminum	6.5 ± 2
Silicon	18.5 ± 3
$28 < A < 65$†	13 ± 3
(Fe, Co, Ni)	> 3
$A < 65$	< 0.5

*Excluding hydrogen, helium, and lithium. These numbers have been normalized to approximately 100 percent. †This group includes, for example, S, K, Ca, Fe, Co, Ni.

(above background) beyond channel 73 indicates a relatively low abundance of elements of mass number heavier than 65. Similarly, the high-energy proton spectrum (above channel 60) is characteristic of protons from aluminum.

The observed alpha and proton spectra have been analyzed thus far by a computer into the spectra of only eight elements: C, O, Na, Mg, Al, Si, "Ca," and "Fe." The "Ca" stands for elements with $28 < A < \sim 45$, and "Fe" represents elements with $\sim 45 < A < 65$, where A stands for the mass number of the element. Figure 2, A and B, shows the agreement between the observed data (after subtraction of the background and heavy-element contribution) and the computer-calculated results. Analysis into only eight elements represents the data with very few systematic deviations. One of the regions of poor fit is between α-channels 63 and 74.

The results obtained in this way on the chemical composition of the lunar surface are presented in Table 1. The errors quoted are the present estimates of the reliability of the results; the statistical errors are much smaller. The most abundant element on the lunar surface, as on the earth, is oxygen. More than half of all the atoms are of this element. Second in importance, as on the earth's crust, is silicon. Next in abundance is aluminum (*4*), and the quantity of magnesium is somewhat lower. At this stage, only upper limits can be placed on the amounts of carbon and sodium present. The data indicate surprisingly large amounts of elements heavier than silicon. Although a breakdown of these elements cannot be made at present, it is possible to place a lower limit of 3 percent on the combined abundance of Fe, Co, and Ni, and an upper limit of 0.5 percent on that of still heavier elements. The chemical analysis, therefore, indicates that the sample analyzed is a silicate rock similar to materials available on the earth.

Although an elemental analysis (even one more precise than the present one) can be only a rough indicator of detailed rock type, it is of interest to compare the present results with the chemical composition of some materials that have been considered as constituents of the lunar surface). In Fig. 3, where a comparison of the present results is made with the analyses of average dunites, basalts, granites, tektites, chondritic meteorites, and basaltic achondrites (*5*), the comparison shows that the lunar surface at the Surveyor V landing site cannot consist entirely of material similar to chrondritic meteorites or to ultrabasic rocks such as dunite. Tektitic or granitic materials are more consistent with the present estimates of errors, although these materials are apparently ruled out by the γ-ray measurements of Vinogradov *et al.* (*6*). Of the comparisons in Fig. 3, the closest agreement appears to be with the chemical composition of basaltic achondrites and with that of terrestrial basalts.

Figure 3 represents only a few of all possible comparisons. Such comparisons will be even more meaningful when the data obtained by Surveyor V have been completely processed. However, even now, the results provide experimental information on the chemical environment on the surface of the moon, the possible raw materials there, and clues to the history of this longtime partner of the earth.

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2. A. Turkevich, K. Knolle, E. Franzgrote, J. H. Patterson, *J. Geophys. Res.* **72** 831 (1967).
3. *Surveyor V Mission Report, Parts I to III, JPL Technical Report* (Jet Propulsion Laboratory, Pasadena, California, 1967); see also L. D. Jaffe and R. H. Steinbacher, *Science*, this issue.
4. Consideration has been given to the possibility that the high value of aluminum observed in this experiment was due to contamination from the main retro rocket which had aluminum powder in its fuel. Estimates from the known burnout height of this motor and trajectory of the spacecraft after burnout indicate that this source of aluminum contributes less than 0.5 atomic percent to the observed aluminum abundance.
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Surveyor V: Lunar Surface Mechanical Properties

Abstract. *The mechanical properties of the lunar soil at the Surveyor V landing site seem to be generally consistent with values determined for soils at the landing sites of Surveyor I and III. These three maria sites are hundreds of kilometers apart. However, the static bearing capability may be somewhat lower than that at the previous landing sites (2 × 10^5 to 6 × 10^5 dynes per square centimeter or 3 to 8 pounds per square inch). The results of the erosion experiment, the spacecraft landing effects, and other observations indicate that the soil has significant amounts of fine-grained material and a measurable cohesion.*

The Surveyor V terminal landing maneuver resulted in nominal landing velocities of 4.2 m/sec vertically and 0.5 m/sec horizontally. After the initial touchdown, the spacecraft slid about 0.8 m before reaching its final position on a 20-degree slope. The trench dug by one of the footpads during landing is shown in Fig. 1. As indicated by the appearance of the disturbed soil, the penetration into the soil by the footpads during landing, and landing loads in the leg shock absorbers, the mechanical properties of the lunar soil at the Surveyor V landing site seem to be generally consistent with values determined for the soils at the Surveyor I (*1*) and III (*2*) landing sites. However, the values for static bearing capability of the lunar soil at the landing site may be somewhat lower than the previous range of values, which is 2 × 10^5 to 6 × 10^5