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COMBINED X-RAY NEUTRON EXPERIMENT FOR THE EXPLORATION OF LUNAR AND PLANETARY SURFACES

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ABSTRACT

A combined X-ray fluorescence and neutron excitation experiment for obtaining rapid surface and subsurface element analysis is presently under investigation. The X-ray experiment would utilize both alpha and beta sources; the neutron experiment would utilize isotopic or accelerator neutron sources. The X-ray system would sample element composition to micron depths, whereas the neutron method would measure element composition to approximately 2 feet in depth. Differences in element composition for the two measurements may reveal the time scale of processes involved in the formation of the planetary surfaces.

Measurements with the X-ray and neutron sources have been carried out, and quantitative and semiquantitative results have been obtained. A preliminary design of a combined system has been completed and is presently under construction.

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1. INTRODUCTION

A major goal of geochemical exploration of the moon and planets is the mapping of these planetary surfaces with respect to their element compositions. Information concerning both the areal and vertical composition distribution is of great interest in such exploration programs. These geochemical maps can be used, for example, in the study of processes such as differentiation and erosion of planetary surfaces, and the interaction of the solar wind with these surfaces.

A simultaneous areal and vertical study of the element composition of planetary surfaces can be carried out through the study of gamma-ray, X-ray, and α-particle emissions. These emissions can be produced either by natural radiation (such as the decay of ^{40}K, U, and Th) or by the incident cosmic rays and solar X-rays interacting with the surface, or they could be induced by a variety of excitation sources placed on the surface during unmanned or manned space flight missions.

The natural emissions produced by cosmic rays and solar X-rays can be detected most efficiently from a spacecraft orbiting about a planetary surface. The X-rays detected would be characteristic of the element composition of the surface extending possibly to a depth of 10 microns. The discrete gamma-ray spectrum should characterize the element composition to a depth of approximately 2 feet. Because the spacecraft would be in orbit about the planet, areal element composition could be obtained. A comparison of the element composition (inferred from an analysis of the X-ray emissions) with that obtained from an analysis of the gamma-ray emissions would possibly yield information on the vertical element distribution. (This experiment will be performed during the Apollo 15 and 16 missions.)

If the source, sample, and detector geometry can be controlled and the intensity of the excited emissions can be increased over that which can be obtained from orbital measurement, then more precise information about element composition can be obtained. X-ray fluorescence and neutron excitation sources that can be carried to a planet may provide the means to perform such measurements. Some possible and promising experimental approaches will be discussed in this paper.

2. X-RAY FLUORESCENCE EXPERIMENT

Radionuclides provide a very effective energy source for the excitation of characteristic X-ray spectra. The generated spectra can in turn be detected by an energy-sensitive detector such as a proportional counter, scintillation detector, or solid state detector. (In the application to be described, a proportional counter is chosen because of its reliability, ease of operation, and energy resolution.) The output of the proportional counter is fed to a multichannel analyzer which produces a pulse-height spectrum. The pulse-height spectrum is reduced to an energy spectrum which, in turn, is converted to compositional information (Reference 1).

The proposed experiment is based on the latest data about lunar materials (Reference 2). By the combinination of three radioactive sources with two proportional counters, it will be possible to cover the element range from Zr to Mg with sensitivities of the order of 1 percent or better.

A thin-window proportional counter (1-mil Be) will be used in combination with an α emitter (^{210}Po or ^{242}Cm) to cover the element range from Mg through Ti. Examples of characteristic spectra of dunite and granite produced with a ^{242}Cm source are shown in Figure 1.

A second proportional counter will be used alternately with ^{55}Fe and ^{109}Cd. Excitation with the 6-keV X-rays of ^{55}Fe (Mn Kα line) should give optimum coverage from Ti through K; ^{109}Cd, with its 22-keV X-rays (I Kα line), will be used to excite elements from Zr through Fe.

The sensitivity of the proportional counters will be maximized by the selection of appropriate gas fills: Ne for the light elements and Xe for the heavier elements.

The instrument system is designed for sequential measurements so that only the light-element detector is active when the α source is used. A conceptual design of the detector system is shown in Figure 2.

The plan is for the astronaut to carry the experiment to various sites, either by hand or with a roving vehicle. The estimated earth weight of the package will be 20 lb or less. Measurements of a rock or some other terrain feature can be made by placing the analyzer on the surface or in contact with the feature. Although no sample preparation is visualized, a smoothing of the surface by the astronaut could be useful.

The analog output from the sensors and amplifiers will be processed by either a 64- or a 128-channel ADC converter and fed to a data accumulator with a capacity of 4096 words. The spectrum will then be read out in real time through a pulse code modulated transmitter to earth for on-line data analysis, and the analyzed data will be returned to the astronaut in approximately 10 to 12 minutes after initiation of the measurement. The results of an analysis showing the contribution of each element component to the total envelope of a spectrum produced with a ^{242}Cm source are indicated in Figure 3.

3. NEUTRON-GAMMA TECHNIQUES

Neutron-induced excitation methods for chemical analyses and mineral explorations using both isotope and accelerator neutron sources have been under investigation by NASA and the U.S. Geological Survey (see, for example, References 3, 4, 5 and 6). The accelerator source has been developed to measure the major element composition, hydrogen content, and bulk density. This is accomplished by the measurement of gamma rays produced by inelastic scattering, radiative capture, activation, and neutron "die away". The best approach for this particular application, however, is to use isotopic sources and to measure the gamma rays produced by neutron radiative capture and activation. Sensitivities and energies of thermal neutron capture have been tabulated for most of the elements (Reference 7). Because an isotopic source cannot be turned off, the counting is done simultaneously with the irradiation cycle. This latter approach allows analysis not only of the major element composition but also of some minor and trace elements.

Figure 4 shows a cross section of a neutron accelerator developed for space flight application. Figure 5 shows a configuration of an accelerator detector and a shield for a lunar mission. Figure 6 shows two configurations possible for lunar application that use an isotopic Cf^{252} neutron source. Figure 7 shows a pulse-height spectrum obtained with a Ge(Li) detector that uses a configuration similar to that shown in Figure 6B.

Because Ge(Li) detectors will not survive the rigors of space environment, NaI(Tl) detectors are needed. Resolution is considerably poorer for NaI(Tl) than for Ge(Li), but computer techniques can partially compensate for this fault. A rather sophisticated analytical procedure has been developed to obtain both qualitative and semiquantitative information from the measured spectrum.

A pulse-height spectrum of gamma rays resulting from radiative capture, activation, and natural background is shown in Figure 8 (curve a). This spectrum was obtained with a 3- by 3-in. NaI(Tl) crystal and a large sample of basalt that had been irradiated by a pulse neutron generator.* The pulse-height spectrum shown covers the energy region from 0.2 to 3 MeV. Similar spectra have been obtained with a ^{252}Cf source.

Certain lines can easily be identified in Figure 8 (curve a), but other lines are masked by the background and the continuum caused by the scattering of the induced gamma rays in the irradiated material. It is the discrete lines that contain the information on element composition. The analytical procedure is outlined in Figure 8 and the qualitative results are indicated. The details of the method can be found in Reference 4.

Experiments with neutron sources indicate that the bulk element composition down to approximately 2 feet can be sampled by the techniques described above. The combination of the X-ray fluorescence system with either of the neutron methods described above gives information about element composition and also some information on vertical distribution.

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*J. Reed, private communication, 1968.

4. MULTIPLEX DATA ACCUMULATOR

A key to the combined neutron-gamma and X-ray experiment is a compact data control, acquisition, and transmission system that will operate the experiment, convert the analog signal to digital data, and prepare the data for transmission. Furthermore, if an astronaut is to use the equipment, returning of the information after analysis will be an aid to decision making and control of the experiment. Toward this end, a so-called multiplex data accumulator (MDA) is under development at Goddard Space Flight Center.

The first step in the development of the MDA was the construction of a 4096-channel analyzer with a 512 ADC. Figure 9 is a photograph of the analyzer. The system contains a preamplifier-amplifier input, an anticoincidence system, the 512 ADC, a 4096-word (16-bit) memory, and two high-voltage supplies. The unit shown in the photograph is portable and is powered by 28-V batteries. Eight 512-channel spectra can be stored.

The above system is now being extended to include the following MDA concept. The MDA is designed around a high-speed, common-bus access system, and is called a memory scanner (Figure 10). The neutron-gamma experiment requires extremely fast timing control (in the 1-MHz region); therefore, the scanner and bus must be capable of operating at speeds in excess of 1 MHz so that such an experiment might be controlled. These speeds will also enable the MDA to control the sorting of data from a number of different experiments simultaneously, perform data compression, and read out the data to an output interface such as a telemetry system. The scanner will scan the devices attached to the bus (i.e., experiments, I/0 units, and housekeeping units) and process the requests from the devices on a priority basis. The scanner will be designed to initiate certain programmed functions in the experiments by sending the proper commands to the specific experiments. The scanner should also have the capabilities of allocating various amounts of memory to the different experiments, and performing housekeeping functions by the use of some limited amount of software. An engineering model of this system should be available in late 1971. With the MDA, the excitation sources, and the detectors, the combined experiment considered in this paper should be feasible.

5. ON-LINE DATA ANALYSIS

The system has an on-line data analysis sytem which allows rapid analysis of the raw data and returns the interpreted data to the investigator (e.g., the astronaut) in the field. The details of the system have been described in a number of papers (References 1, 8, and 9).

The methods described have been developed for use on the CDC 3200 and IBM 360 computers. Recently, through use of the IBM 2250 system (a system with a CRT display and a light pen in conjunction with an IBM 360 Model 91 computer), a method has been developed that allows the analyst to have real-time control of the computer throughout the analysis. Figures 11 through 13 are photographs taken of the CRT tube during the operation of the program; they give an idea of how the on-line system works. A complete description is beyond the scope of this paper.

The first step in the analysis requires that the investigator select the function to be performed. The options are as follows:

(1) Raw data and standards input. Using standard spectra, the system (as presently constructed) synthesizes the raw spectra. The analysis supplies the relative magnitude or intensity of each standard spectrum required to synthesize the raw data spectrum most adequately (based on least-squares criteria). The absolute or relative element composition corresponding to those elements in the standard library may then be inferred.

(2) Data storage. This allows the investigator to store the raw data for later analysis.

(3) Data display. Three spectra can be simultaneously displayed and compared.

(4) Background spectrum. This option allows a background spectrum to be read in.

(5) The weighting function, omega. This option allows the analyst to read in statistical weighting functions calculated outside the main program. Under certain conditions, the statistical weighting functions can be calculated in the main program.

Once the functions described above are complete and a least-squares analysis is performed, the results of the analysis are displayed. The results shown in Figure 12 were obtained after a mixture of the elements listed was irradiated in a nuclear reactor. Finally, from the results shown in Figure 12, the pulse-height spectrum was calculated with the standard library spectra. The results are compared with the raw pulse-height spectrum. Raw data, and the difference between the actual and calculated spectra, are displayed in Figure 13.

This system has been used successfully to analyze gamma-ray, X-ray, α-particle, and mass spectroscopy pulse-height spectra.

6. CONCLUSION

A combined X-ray and neutron-gamma-ray system holds great promise for lunar element and planetary surface element composition analysis. This experiment can use alpha and X-ray sources to produce X-ray fluorescence of surfaces. It is believed that composition analyses can be obtained for elements from Na through Zn. In addition, both accelerator and isotopic neutron sources can be used to perform element analysis for the major and some minor and trace elements. The X-ray system yields information down to micron depths, whereas the neutron methods yield information down to approximately 2 feet. A comparison of results from the two measurements should yield information about vertical composition distribution in lunar and planetary surfaces.

The system now under development includes the excitation sources, detectors and associated electronics, a multiplex data accumulator, and an on-line data analysis system. Much of the system is complete, but a total system should be available for test in late 1971.

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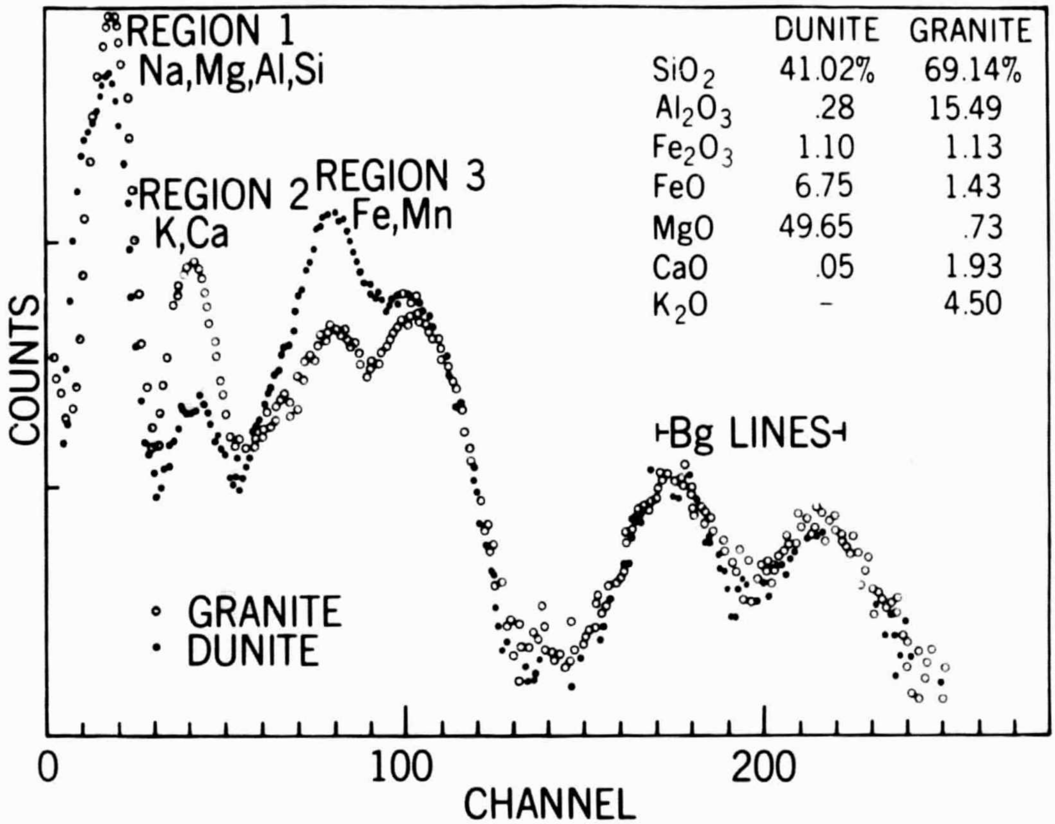

Figure 1–Comparison of pulse height spectra with dunite and granite samples. A ^{242}Cm excitation source is used.

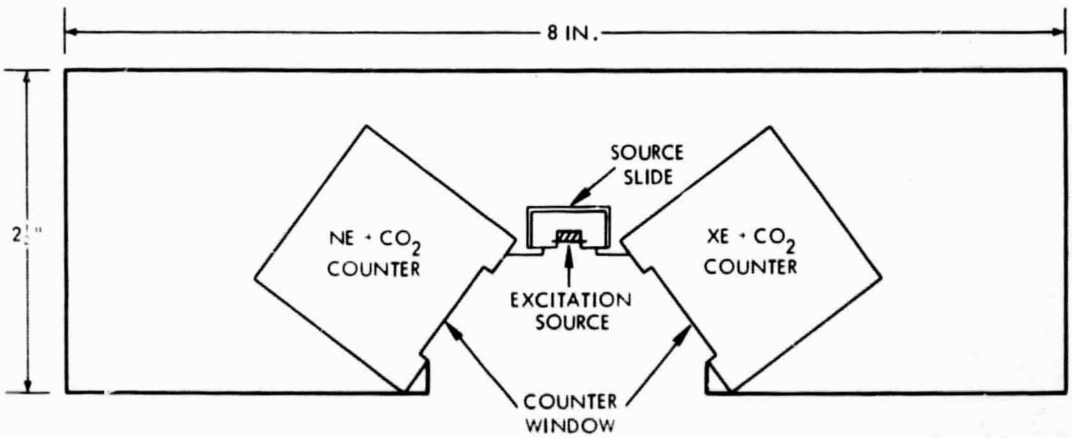

Figure 2–Excitation sources and sensors subsystem for lunar exploration X-ray fluorescence analyzer.

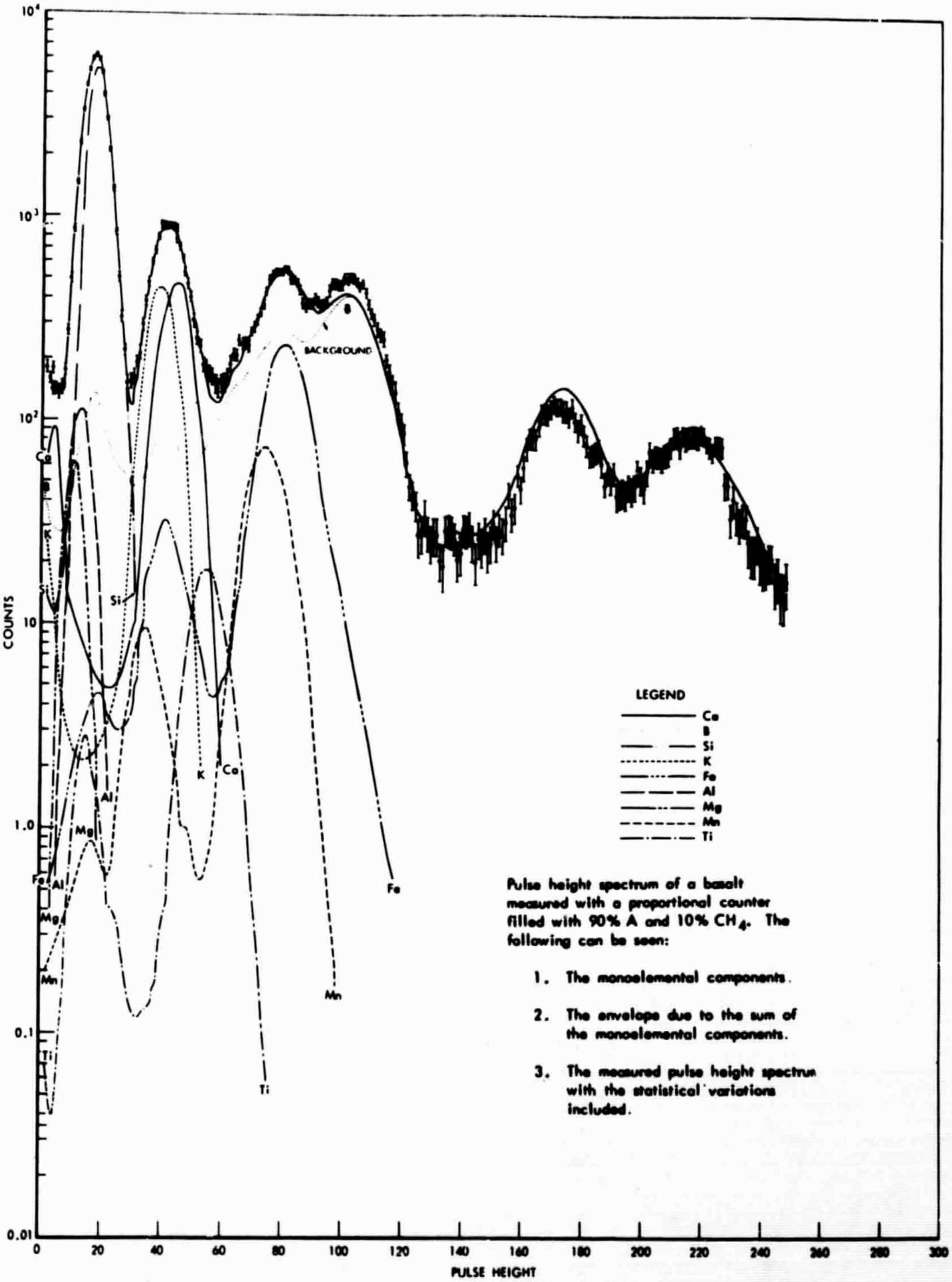

Figure 3–Results of the analysis of a pulse-height spectrum of basalt.

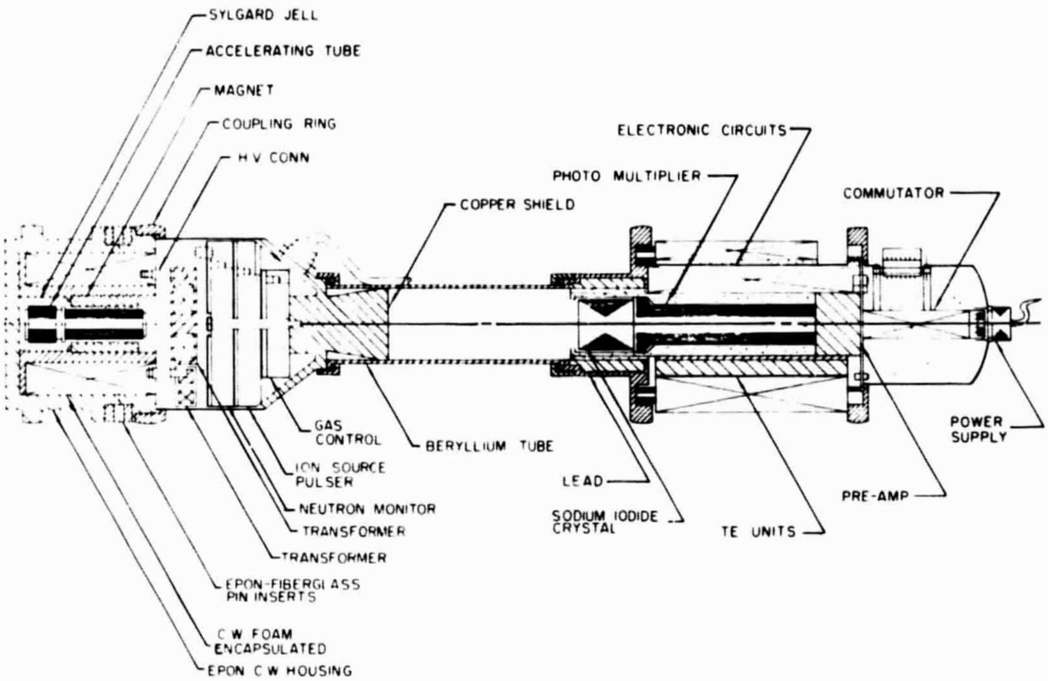

Figure 4—Cross section of a neutron accelerator for space flight application.

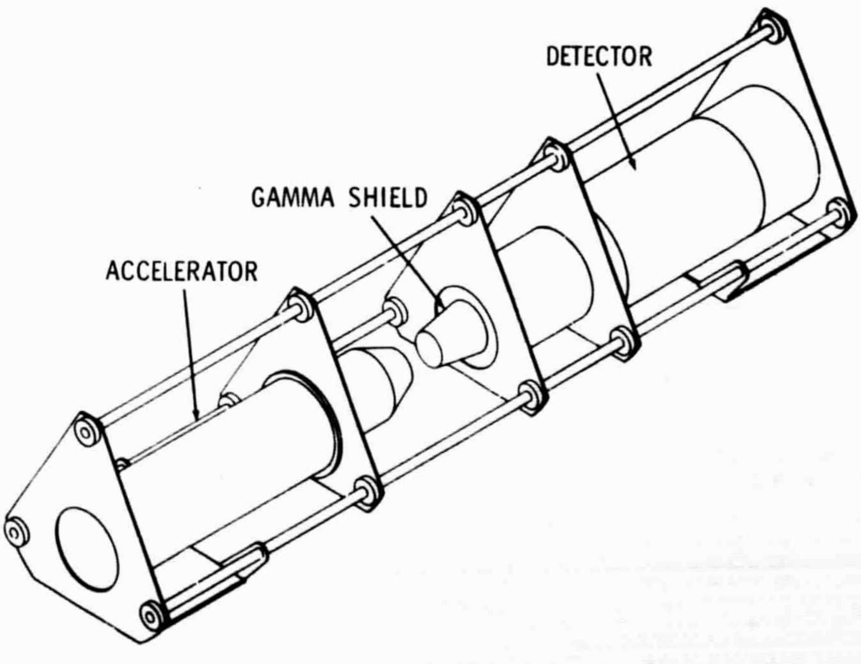

Figure 5—Combined neutron experiment detector probe.

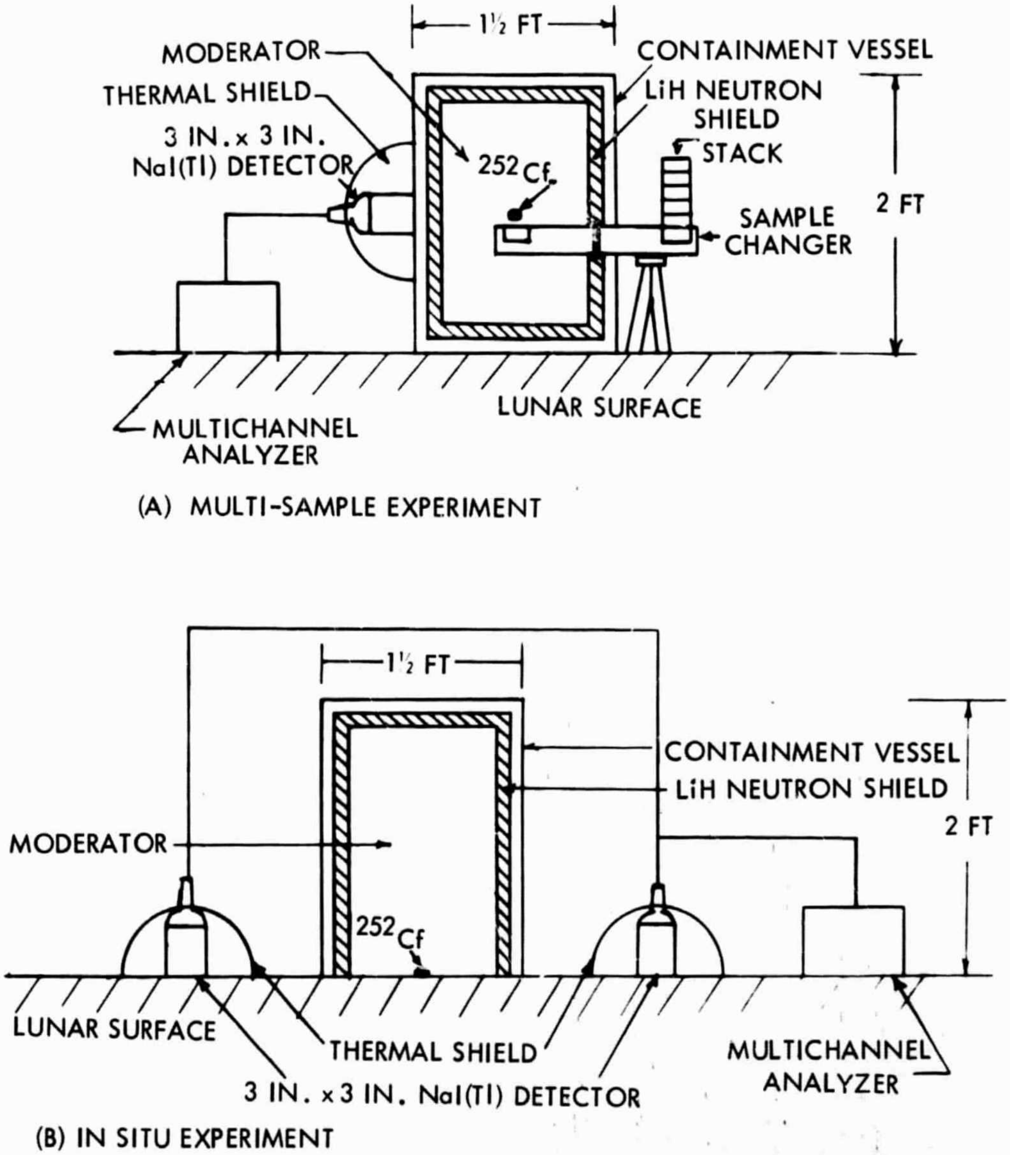

Figure 6–Two possible configurations using isotopic neutron sources.

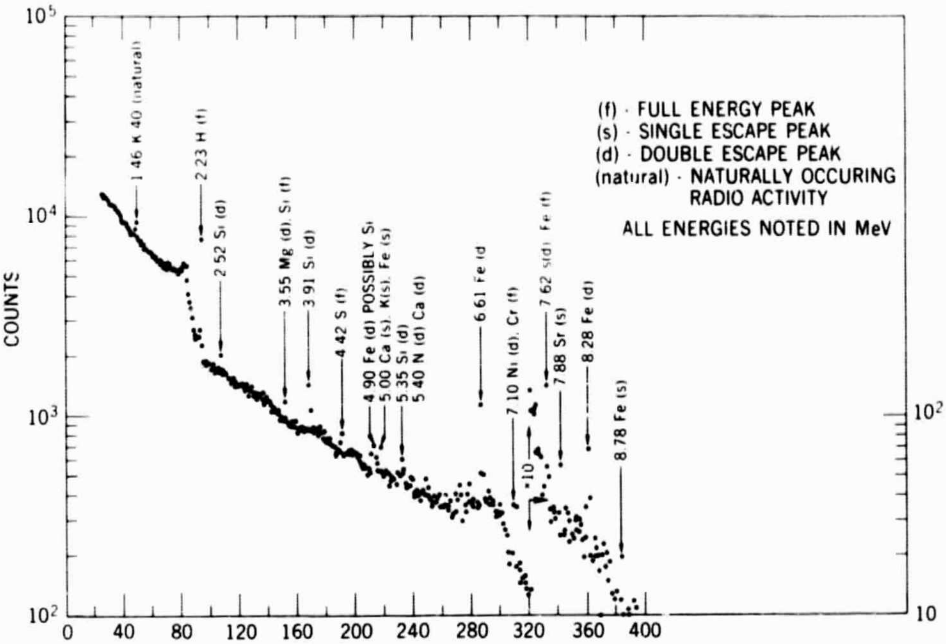

Figure 7–Prompt capture and activation gamma pulse-height spectrum using ^{252}Cf source and solid state detector [35-cm ^{2} Ge (Li)].

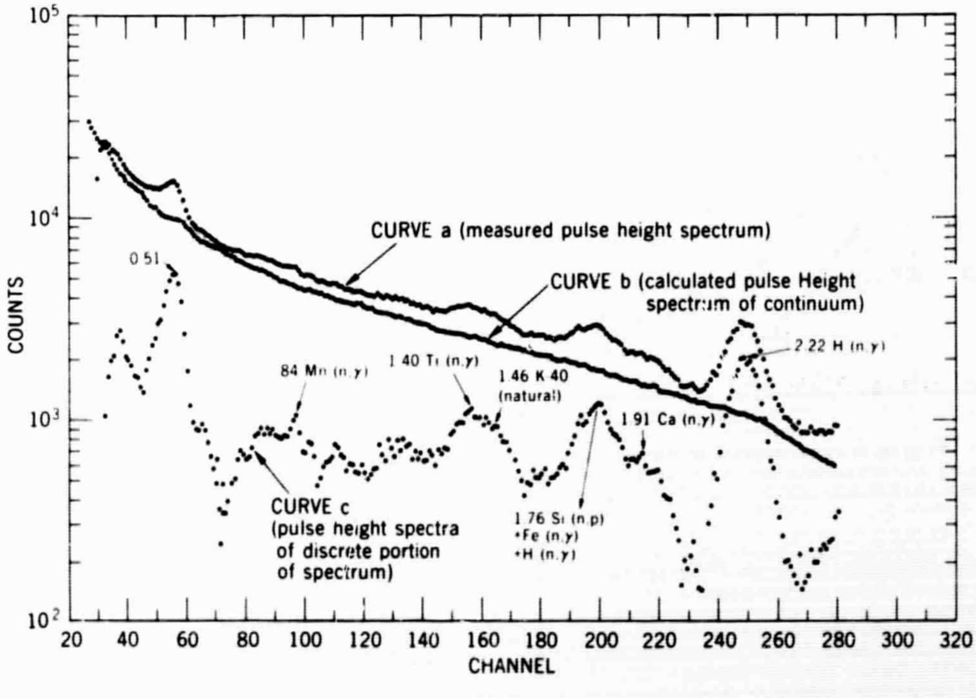

Figure 8–Pulse-height spectra of basalt sample irradiated with an accelerator source.

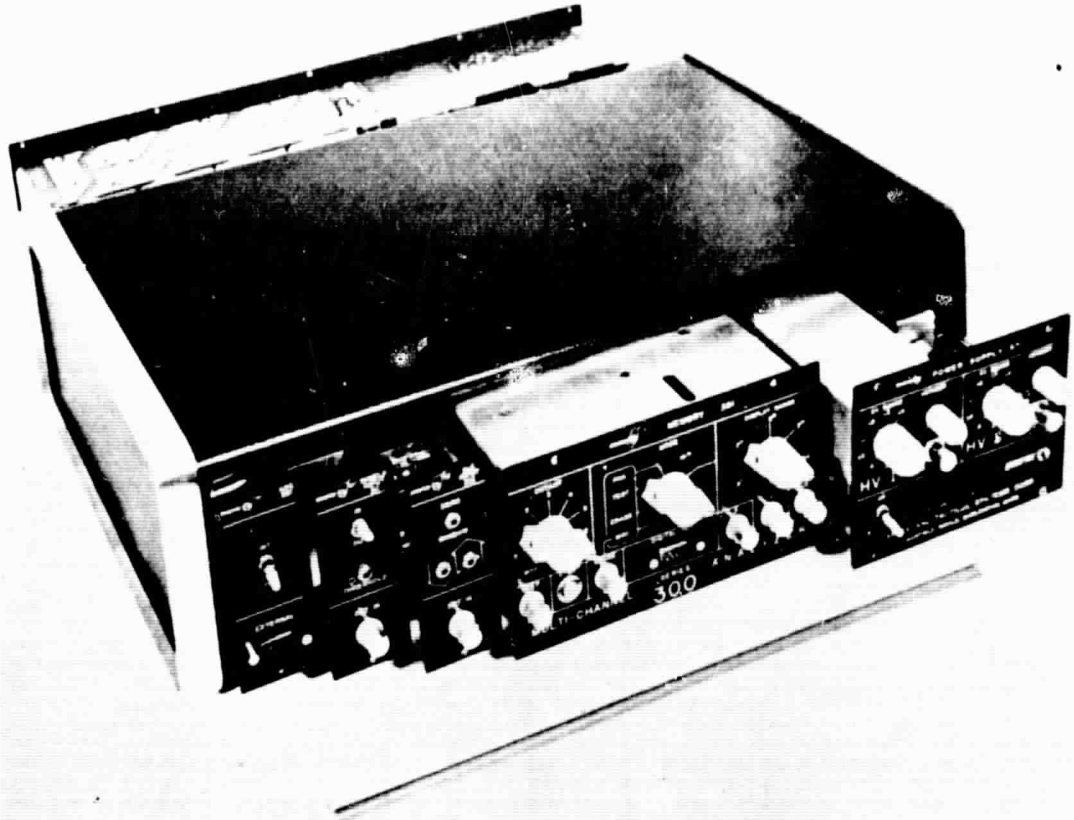

Figure 9a–Engineering model of a possible 512-channel pulse-height analyzer.

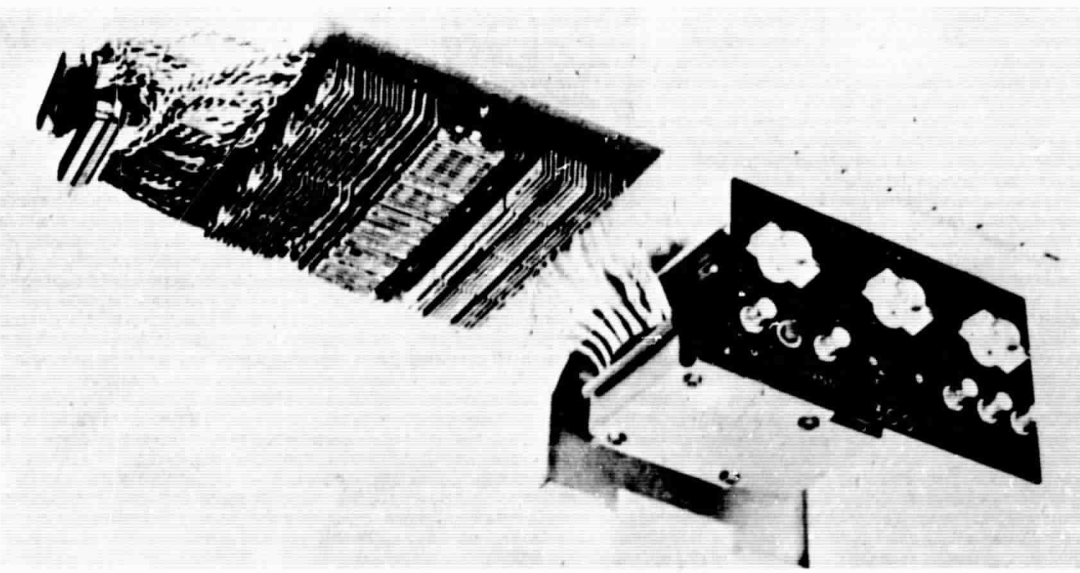

Figure 9b–View of the 4096 memory unit.

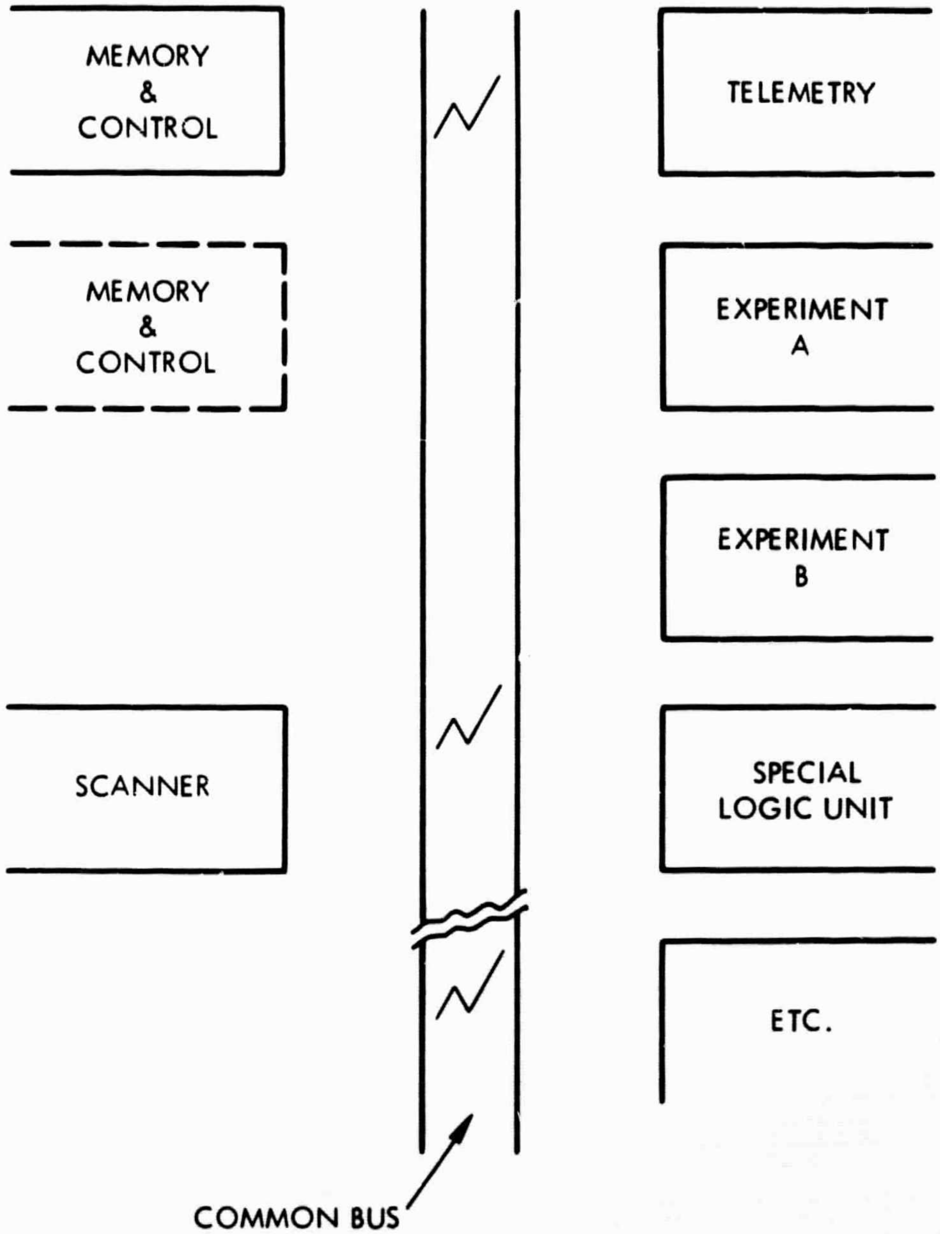

Figure 10–Simplified block diagram for multiplexed data accumulator.

SELECT THE FUNCTION THAT IS TO BE PERFORMED

* INPUT THE LIBRARY/RAW DATA
* SAVE THE DATA
* DISPLAY THE DATA
* ANALYZE THE DATA
* PREPARE THE LIBRARY

* REWIND THE INPUT DATA
* STOP EXECUTION

Figure 11–Options from IBM 2250 CRT Jisplay.

COMPONENT	INTENSITY	ERROR	PERCENT
NA	20.063995	0.663805	3.3084
CL	12.746380	0.797515	6.2568
K	9.050738	0.621223	6.8638
MN	4.348515	0.657436	15.1186
SC	4.555974	0.506255	11.1119
A	-0.558494	0.500723	0.0
AS	11.503031	0.655179	5.6957
CU	3.572647	0.573003	16.0386
CR	4.814013	0.439682	9.1334
I	0.748814	0.351079	46.8847
LA	4.098229	0.431197	10.5216

INDICATE BELOW
TO CONTINUE
PROCESSING

* CONTINUE

Figure 12–Least squares analysis results displayed on IBM 2250 CRT.

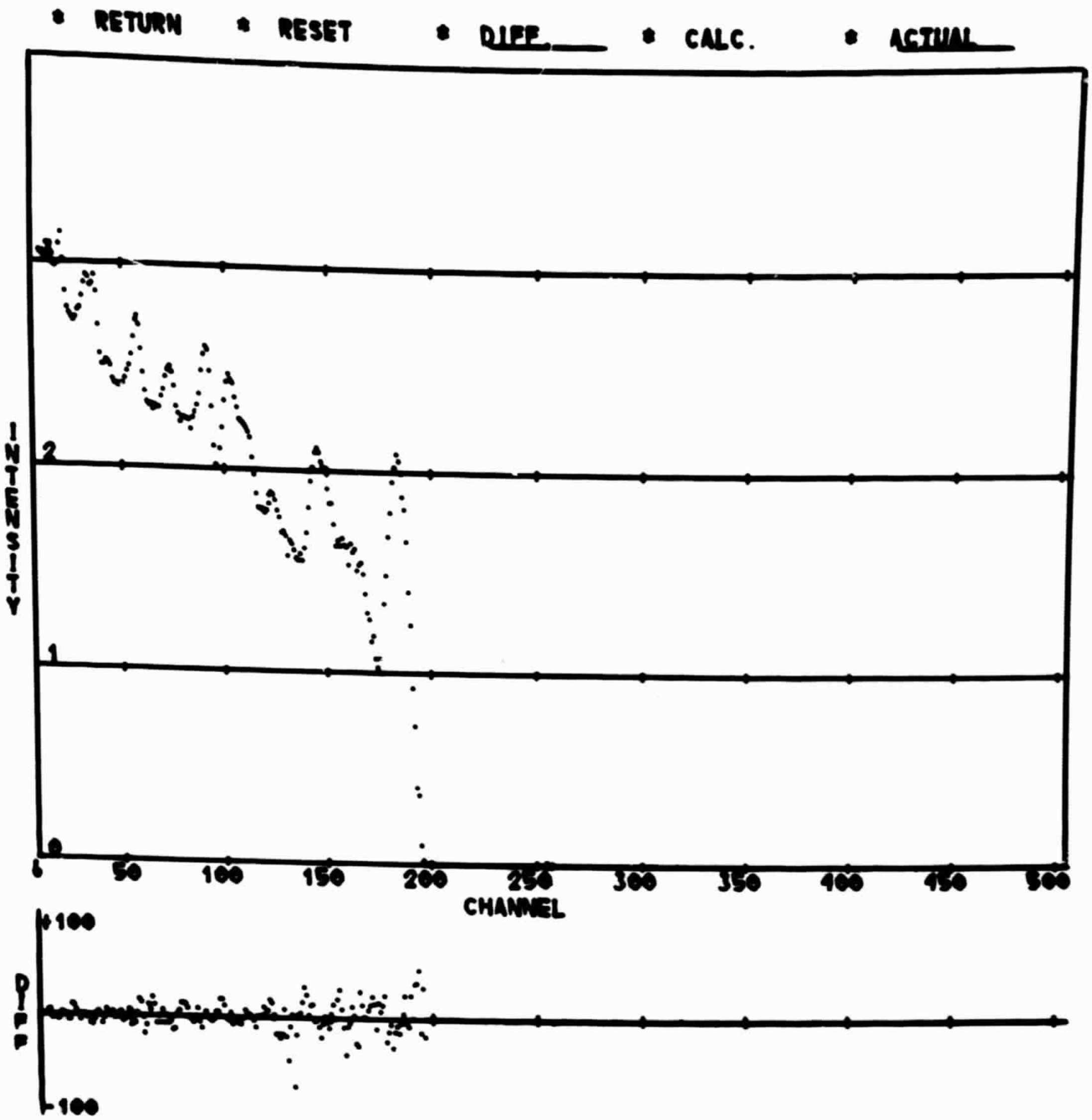

Figure 13–The actual spectrum and the difference between it and the calculated spectrum, from the results shown in Figure 12, as displayed on IBM 2250 CRT.